National Rehabilitation Information Center

reSearch

A collection of research reviews on rehabilitation topics from NARIC and other information resources.

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Brain-Computer Interface Technology

In this edition of *reSearch* we explore the topic of brain-computer interface (BCI), looking at some of the latest developments and their potential benefit to people with disabilities. *reSearch* was originally created as a vehicle to further explore disability related topics presented by patrons through our information service via phone, mail, email, and our chat-based reference service. In May, NARIC received an emailed request for information on BCI:

> … I am currently doing a journalism course and am doing some freelance work for hopeful publication in the future. My current story is a feature article on the benefits of technology, especially in medicine. In particular, Brain Computer Interfaces, which are basically computers which are made to help people, like making someone who is paralyzed able to control a machine through thought and by doing so increasing the individuals mobility and independence. I was wondering if you could let me know what you think the benefits of technology like this are to people suffering from spinal injury and the future implications.

In June, NARIC exhibited at the annual conference of the Rehabilitation Engineering and Assistive Technology Society of North America (RESNA), where we had the opportunity to meet researchers in this exciting field.

Brain-computer interface technologies—abbreviated BCI throughout this document—offer persons with disabilities new opportunities for rehabilitation, and expanded use of adaptive and assistive devices, especially for individuals with neurological and communication disorders such as locked-in syndrome (LIS) or amyotrophic lateral sclerosis (ALS). (See *reSearch, 1*(4), September 2006 at www.naric.com/public/reSearch/ReSearchVol1no4A.cfm for more information on LIS.) BCI technologies provide a direct connection between the user's brain and computer device, either through implantation of electrodes in the brain or electrodes placed on the scalp similar to an electro encephalogram (EEG). This connection can be one way from either the computer device to the user or the user's brain to the computer. Two-way BCI technologies allow for communication between the computer device and the user. Additionally, BCI technology can be used in combination with prosthetics and orthotics to restore more natural limb functioning. (For more information on best practices in prosthetics and orthotics see *reSearch 1*(2), June 2006 at www.naric.com/public/reSearch/ReSearchVol1no2.cfm.)

Originally, we were going to explore research on BCI over a 10-year period. However, the wealth of new research published since 2003 provided an ample "snapshot" of the latest innovations in BCI. Our main search terms included brain-computer interface, direct neural interface, brain machine interface, neural assistive technology, and various others. A listing of approximately 150 additional descriptor terms between the NARIC, ERIC, Cochrane Collaboration, and PubMed databases can be found at the end of this document.

A search of the REHABDATA database resulted in five documents published between 2003 and 2007. The ERIC database search resulted in one document from 2006; and the Cochrane Collaboration resulted in nine documents published between 2004 and 2006. Finally, a search of PubMed resulted in 70 documents published between 2003 and 2008. The complete citations are included in this research brief.

Table of Contents

NIDRR Funded Projects Related to Brain-Computer Interface and Related Assistive Technologies

In addition to document searches, we searched our NIDRR Program Database to locate grantees/projects related to brain-computer interface and related assistive technologies. The search resulted in nine NIDRR funded projects—five currently funded and four which have completed their research activities. Project information and their publications are offered as additional resources for our patrons.

assitivetech.net - Internet Site on Assistive Technology.
Project Number: H224B020002 *(Former NIDRR grantee, now funded through RSA).*
www.assistivetech.net

Development of a Neural-Machine Interface for Lower-Limb Prosthesis Control.
Project Number: H133F080006
www.ric.org/research/centers/necal/staff/Huang.aspx

Rehabilitation Engineering Research Center on Communication Enhancement.
Project Number: H133E030018
www.aac-rerc.com

RERC on Rehabilitation Robotics and Telemanipulation Machines Assisting Recovery from Stroke Rehabilitation Engineering Research Center (MARS-RERC).
Project Number: H133E020724
www.smpp.northwestern.edu/MARS/mars.html

Rehabilitation Engineering and Assistive Technology Society of North America (RESNA).
Formerly a NIDRR grantee and currently funded through the Rehabilitation Services Administration (RSA).
www.resna.org/projects

Provides technical assistance to Statewide AT Programs (http://69.89.27.238/~resnaorg/taproject/RESNA.html) funded under the AT Act of 1998, as amended.

Provides technical assistance resources for financial loan programs Alternative Financing Programs (AFP) (http://69.89.27.238/~resnaorg/AFTAP/RESNA.html) funded under Title III of the AT Act of 1998 and those associated with statewide AT programs.

The following projects have completed their research activities. Their reports and articles are available through NARIC's document delivery service:

Assistive Computer Interfaces for Persons with Movement Disorders.
Project Number: H133G30064
Phone: 410/955-7093

Direct Brain Interface for Control of Assistance Technology.
Project Number: H133G70120
Phone: 734/936-7170

Machine-Vision Recognition of Emblematic Facial Expressions to Facilitate Human Computer Interaction.
Project Number: RA94129001
Phone: 703/731-0655

Multi-Modal, Configurable User Interface for Persons with Disabilities.
Project Number: RW96013006
Phone: 703/760-9720

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Documents from NARIC's REHABDATA search listed are listed below:

2007

(2007). **Mobility and more.** *PN/Paraplegia News, 61*(8), 15-16.
NARIC Accession Number: J52832
ABSTRACT: Article presents recently developed technology to assist people with communication and mobility impairments including a device that turns thoughts into spoken words, a mind controlled wheelchair, and two-gear wheelchair wheels. Michael Callahan, a graduate student in Systems and Entrepreneurial Engineering at the University of Illinois at Urbana-Champaign, has invented the Audeo, a device that translates neurological signals into spoken words or commands for other devices, such as a power wheelchair. He has also created an application that compares signals from neck muscles and developed a fully functional wheelchair prototype that can be controlled by a person's thoughts.

The article also discusses Magic Wheels, all mechanical, two-geared wheels that replace the standard spoke, mag, or power-assist wheels on manual wheelchairs. In regular gear, Magic Wheels reportedly work the same as standard wheelchair wheels. When shifted into low gear, they are similar to a two-speed bicycle, making it easy to push when climbing hills or ramps or rolling over uneven surfaces. Magic Wheels also have an automatic hill-holding feature so that users won't roll backward between pushes.

2006

Branner, Almut; Caplan, Abraham, H.; Chen, David; Donoghue, John, P.; Friehs, Gerhard, M.; Hochberg, Leigh, R.; Mukand, Jon, A.; Penn, Richard, D.; Saleh, Maryam; & Serruya, Mijail, D. (2006). **Neuronal ensemble control of prosthetic devices by a human with tetraplegia.** *Nature, 442*(7099), 164-171.
NARIC Accession Number: J53625
ABSTRACT: Article presents results from a pilot clinical evaluation of a BrainGate (Cyberkinetics, Inc.), a neuromotor prosthesis (NMP) in a man with tetraplegia. An NMP is a type of BCI designed to restore lost motor function in paralyzed humans by routing movement-related signals from the brain to external effectors. NMPs require that intention-driven neuronal activity be converted into a control signal that enables useful tasks. Neuronal ensemble activity recorded through a 96-electrode array implanted in the subject's primary motor cortex demonstrated that intended hand motion modulates cortical spiking patterns three years after spinal cord injury. Decoders were created to produce a neural cursor with which the subject opened simulated e-mail and operated devices such as a television. The subject also used neural control to open and close a prosthetic hand, and perform basic tasks with a multijointed robotic arm.

Redstone, Fran. (2006). **A training program for the use of the Cyberlink control system for young children with cerebral palsy.** *Technology and Disability, 18*(3), 107-115.
NARIC Accession Number: J52044
ABSTRACT: Study evaluated the use of the Cyberlink with two five- and four-year-old children with cerebral palsy, both of whom were nonverbal. Cyberlink is a computer interface that is attached to the user's forehead in order to interpret brain waves, minute facial movements, and eye movements. A training program was developed using the Cyberlink to teach mouse clicking and cursor control techniques, as well as use of the cursor for games and augmentative and alternative communication. The results indicated that both participants learned to control the cursor adequately, as individualization of the stimuli for each child and the flexibility of the software were determined to be key indicators of program success.

2003

BeMent, S.L.; Huggins, J.E.; Kushwaha, R.K.; Levine, S.P.; Minecan, D.N.;Sagher, O.; Schuh, L.A.; & Vaideeswaran, J. (2003). **Feedback experiments to improve the detection of event-related potentials in electrocorticogram signals.** *In R. Simpson (Ed.), Proceedings of the RESNA 26th International Conference: Technology and Disability: Research, Design, Practice and Policy. Arlington, VA: RESNA Press.*
NARIC Accession Number: O15623
ABSTRACT: Paper describes the use of real-time feedback to improve detection of event-related potentials (ERPs), which are required for the operation of a direct brain interface, in human electrocorticogram signals. A direct brain interface accepts voluntary commands directly from the human brain without requiring physical movement and can be used to operate a computer or other assistive technology. In the first-generation system, feedback to subjects was based on the incremental change in the signal-to-noise ratio of the ERP template. The second-generation system provided subjects with online feedback on the cross-correlation values generated by correlating an ERP template with the continuous electrocorticogram signal. Results showed that with feedback, subjects could learn to improve the detection accuracy of ERPs. This paper was presented at the 2003 annual conference of RESNA, the Rehabilitation Engineering and Assistive Technology Society of North America and is available on CD-ROM.

Good, David, C. (2003). **Stroke: Promising neurorehabilitation interventions and steps toward testing them.** *American Journal of Physical Medicine and Rehabilitation, 82*(10 (Supplement)), S50-S57.
NARIC Accession Number: J46999
ABSTRACT: Article reviews stroke rehabilitation interventions currently being studied as well as treatments that may be candidates for randomized clinical trials in the future. Some of the design and implementation is-

sues related to stroke rehabilitation studies and issues unique to stroke patients are discussed. New techniques to enhance motor recovery that are the subject of recent clinical trials include constraint-induced movement therapy, treadmill training with partial body weight support, robotic training, and bimanual upper limb training. Functional magnetic resonance imaging, positron emission tomography, and high-resolution electro-encephalography have been successfully applied to study neural reorganization after stroke. Pharmacologic interventions, BCI technology, and cell transplantation are also discussed.

Full-text copies of these documents may be available through NARIC's document delivery service.

To order any of the documents listed, please note the NARIC Accession Number (starts with a J, O, or R) and call an information specialist at 800/346-2742.

Or you can order online at www.naric.com/services/requestform.cfm. There is a charge of 5¢ per page for copying and shipping with a $5 minimum on all orders. International shipping fees may apply.

Document from the Education Resource Information Center (ERIC) search at www.eric.ed.gov is listed below:

2006

Hammock, Elizabeth, A.D.; & Levitt, Pat. (2006). **The discipline of neurobehavioral development: The emerging interface of processes that build circuits and skills.** *Human Development, 49*(5), 294-309.
ERIC #: EJ750637
ABSTRACT: The study of neurobehavioral development focuses on the mechanisms through which the experiences of an individual influence the ontogeny of brain circuits that ultimately control complex functions, such as social engagement, mood and emotional regulation and cognition. Advances in experimental approaches and technologies provide opportunities to gather more detailed information about developing behavioral systems. This information is more comprehensive and readily applied in studies utilizing strategies that link the disciplines of developmental neurobiology and psychology. Here, examples are provided to illustrate the hierarchical assembly of neural systems, which incorporate information from the genome and the environment to define the ultimate developmental trajectory of an individual.

Documents from the Cochrane Database of Systematic Reviews search at www.thecochranelibrary.org are listed below:

2006

Birbaumer, N.; Elger, C.; Hill, N.J.; Hinterberger, T.; Kübler, A.; Lal, T.N.; Mochty, U.; Nijboer, F.; Schölkopf, B.; Schröder, M.; Widman, G.; & Wilhelm, B. (2006). **Classifying EEG and ECoG signals without subject training for fast BCI implementation: comparison of nonparalyzed and completely paralyzed subjects.** *IEEE Transactions on Neural Systems and Rehabilitation Engineering, 14*(2), 183-6.
ID: CN-00557088
ABSTRACT: We summarize results from a series of related studies that aim to develop a motor-imagery-based BCI using a single recording session of electroencephalogram (EEG) or electrocorticogram (ECoG) signals for each subject. We apply the same experimental and analytical methods to 11 nonparalysed subjects (8 EEG, 3 ECoG), and to 5 paralyzed subjects (four EEG, one ECoG) who had been unable to communicate for some time. While it was relatively easy to obtain classifiable signals quickly from most of the non-paralyzed subjects, it proved impossible to classify the signals obtained from the paralyzed patients by the same methods. This highlights the fact that though certain BCI paradigms may work well with healthy subjects, this does not necessarily indicate success with the target user group. We outline possible reasons for this failure to transfer.

Gao, S.; Gao, X.; Hong, B.; Wang, R.; & Wang, Y. (2006). **A practical VEP-based brain-computer interface.** *IEEE Transactions on Neural Systems and Rehabilitation Engineering, 14*(2), 234-9.
ID: CN-00557089
ABSTRACT: This paper introduces the development of a practical BCI at Tsinghua University. The system

uses frequency-coded steady-state visual evoked potentials to determine the gaze direction of the user. To ensure more universal applicability of the system, approaches for reducing user variation on system performance have been proposed. The information transfer rate (ITR) has been evaluated both in the laboratory and at the Rehabilitation Center of China, respectively. The system has been proved to be applicable to greater than 90 percent of people with a high ITR in living environments.

2005

Birbaumer, N.; Grether, A.; Hinterberger, T.; Hofmayer, N.; Kübler, A.; Neumann, N.; Pham, M.; Vatine, J.J.; & Wilhelm, B. (2005). **An auditory brain-computer interface based on the self-regulation of slow cortical potentials.** *Neurorehabilitation and Neural Repair, 19*(3), 206-18.
ID: CN-00529434
ABSTRACT: OBJECTIVES: Communication support for severely paralyzed patients with visual impairment is needed. Therefore, the feasibility of a BCI using auditory stimuli alone, based on the self-regulation of slow cortical potentials (SCPs), was investigated. METHODS: Auditory stimuli were used for task and feedback presentation in an SCP self-regulation paradigm. Voluntarily produced SCP responses and measures of communication performance were compared between three groups (total of N = 59) of visual, auditory, and cross-modal visual-auditory modality. Electroencephalogram recordings and training from Cz-mastoids were carried out on three consecutive sessions. Data of 1500 trials per subject were collected. RESULTS: Best performance was achieved for the visual, followed by the auditory condition. The performance deficit of the auditory condition was partly due to decreased self-produced positivity. Larger SCP response variability also accounted for lower performance of the auditory condition. Cross-modally presented stimuli did not lead to significant learning and control of SCP. CONCLUSIONS: Brain-computer communication using auditory stimuli only is possible. Smaller cortical positivity achieved in the auditory condition, as compared to the visual condition, may be a consequence of increased selective attention to simultaneously presented auditory stimuli. To optimize performance, auditory stimuli characteristics may have to be adapted. Other suggestions for enhancement of communication performance with auditory stimuli are discussed.

Birbaumer, N.; Hinterberger, T.; Kotchoubey, B.; Mellinger, J.; & Wilhelm, B. (2005). **A device for the detection of cognitive brain functions in completely paralyzed or unresponsive patients.** *IEEE Transactions on Bio-Medical Engineering, 52*(2), 211-20.
ID: CN-00502679
ABSTRACT: Unresponsive patients with remaining cognitive abilities may be able to communicate with a BCI such as the Thought Translation Device (TTD). Before initiating TTD learning, which may imply considerable effort; it is important to classify the patients' state of awareness and their remaining cognitive abilities. A tool for detection of cognitive activity (DCA) in the completely paralyzed was developed and integrated into the TTD which is a psycho-physiological system for direct brain communication. In the present version, DCA entails five event-related brain-potential (ERP) experiments and investigates the capability of a patient to discriminate, e.g., between semantically related and unrelated concepts and categories. ERPs serve as an indicator of the patients' cortical information processing. Data from five severely brain-injured patients in persistent vegetative state diagnosed as unresponsive and five healthy controls are presented to illustrate the methodology. Two patients showing the highest responsiveness were selected for TTD training. The DCA integrated in the TTD allows screening of cognitive abilities and direct brain communication in the patients' home.

Fabiani, G.E.; McFarland, D.J.; Pfurtscheller, G.; & Wolpaw, J.R. (2005). **Conversion of EEG activity into cursor movement by a brain-computer interface (BCI).** *IEEE Transactions on Neural Systems and Rehabilitation Engineering, 12(*3), 331-8.
ID: CN-00492040
ABSTRACT: The Wadsworth electroencephalogram (EEG)-based BCI uses amplitude in mu or beta frequency bands over sensorimotor cortex to control cursor movement. Trained users can move the cursor in one or two dimensions. The primary goal of this research is to provide a new communication and control option for people with severe motor disabilities. Currently, cursor movements in each dimension are determined 10 times/s by an empirically derived linear function of one or two EEG features (i.e., spectral bands from different electrode locations). This study used offline analysis of data collected during system operation to explore methods for improving the accuracy of cursor movement. The data were gathered while users

selected among three possible targets by controlling vertical [i.e., one-dimensional (1-D)] cursor movement. The three methods analyzed differ in the dimensionality of the cursor movement [1-D versus two-dimensional (2-D)] and in the type of the underlying function (linear versus nonlinear). We addressed two questions: Which method is best for classification (i.e., to determine from the EEG which target the user wants to hit)? How does the number of EEG features affect the performance of each method? All methods reached their optimal performance with 10-20 features. In offline simulation, the 2-D linear method and the 1-D nonlinear method improved performance significantly over the 1-D linear method. The 1-D linear method did not do so. These offline results suggest that the 1-D nonlinear or the 2-D linear cursor function will improve online operation of the BCI system.

McFarland, D.J.; & Wolpaw, J.R. (2005). **Sensorimotor rhythm-based brain-computer interface (BCI): feature selection by regression improves performance.** *IEEE Transactions on Neural Systems and Rehabilitation Engineering, 13*(3), 372-9.
ID: CN-00530837
ABSTRACT: People can learn to control electroencephalogram (EEG) features consisting of sensorimotor rhythm amplitudes and can use this control to move a cursor in one or two dimensions to a target on a screen. In the standard one-dimensional application, the cursor moves horizontally from left to right at a fixed rate while vertical cursor movement is continuously controlled by sensorimotor rhythm amplitude. The right edge of the screen is divided among 2-6 targets, and the user's goal is to control vertical cursor movement so that the cursor hits the correct target when it reaches the right edge. Up to the present, vertical cursor movement has been a linear function of amplitude in a specific frequency band [i.e., 8-12 Hz (mu) or 18-26 Hz (beta)] over left and/or right sensorimotor cortex. The present study evaluated the effect of controlling cursor movement with a weighted combination of these amplitudes in which the weights were determined by an regression algorithm on the basis of the user's past performance. Analyses of data obtained from a representative set of trained users indicated that weighted combinations of sensorimotor rhythm amplitudes could support cursor control significantly superior to that provided by a single feature. Inclusion of an interaction term further improved performance. Subsequent online testing of the regression algorithm confirmed the improved performance predicted by the offline analyses. The results demonstrate the substantial value for BCI applications of simple multivariate linear algorithms. In contrast to many classification algorithms, such linear algorithms can easily incorporate multiple signal features, can readily adapt to changes in the user's control of these features, and can accommodate additional targets without major modifications.

2004

Birbaumer, N.; Flor, H.; Grether, A.; Hinterberger, T.; Hofmayer, N.; Kübler, A.; Neumann, N.; Pham, M.; & Wilhelm, B. (2004). **A multimodal brain-based feedback and communication system.** *Experimental Brain Research, 154*(4), 521-6.
ID: CN-00471493
ABSTRACT: The Thought Translation Device (TTD) is a BCI based on the self-regulation of slow cortical potentials (SCPs) and enables completely paralyzed patients to communicate using their brain potentials. Here, an extended version of the TTD is presented that has an auditory and a combined visual and auditory feedback modality added to the standard visual feedback. This feature is necessary for locked-in patients who are no longer able to focus their gaze. In order to test performance of physiological regulation with auditory feedback 54 healthy participants were randomly assigned to visual, auditory or combined visual-auditory feedback of slow cortical potentials. The training consisted of three sessions with 500 trials per session with random assignment of required cortical positivity or negativity in half of the trials. The data show that physiological regulation of SCPs can be learned with auditory and combined auditory and visual feedback although the performance of auditory feedback alone was significantly worse than with visual feedback alone.

Birch, G.E.; Bohringer, R.; Borisoff, J.F.; & Mason, S.G. (2004). **Real-time control of a video game with a direct brain-computer interface.** *Journal of Clinical Neurophysiology, 21*(6), 404-8.
ID: CN-00502182
ABSTRACT: Mason and Birch have developed a direct BCI for intermittent control of devices such as environmental control systems and neuro-protheses. This EEG-based brain switch, named the LF-ASD, has

been used in several off-line studies, but little is known about its usability with real-world devices and computer applications. In this study, able-bodied individuals and people with high-level spinal injury used the LF-ASD brain switch to control a video game in real time. Both subject groups demonstrated switch activations varying from 30 to 78 percent and false-positive rates in the range of 0.5 to 2.2 percent over three 1-hour test sessions. These levels correspond to switch classification accuracies greater than 94 percent for all subjects. The results suggest that subjects with spinal cord injuries can operate the brain switch to the same ability as able-bodied subjects in a real-time control environment. These results support the findings of previous studies.

Celka, P.; & Gysels, E. (2004). **Phase synchronization for the recognition of mental tasks in a brain-computer interface.** *IEEE Transactions on Neural Systems and Rehabilitation Engineering, 12*(4), 406-15.
ID: CN-00504681
ABSTRACT: BCIs may be a future communication channel for motor-disabled people. In surface electroencephalogram (EEG)-based BCIs, the extracted features are often derived from spectral estimates and autoregressive models. We examined the usefulness of synchronization between EEG signals for classifying mental tasks. To this end, we investigated the performance of features derived from the phase locking value (PLV) and from the spectral coherence and compared them to the classification rates resulting from the power densities in alpha, beta1, beta2, and 8-30-Hz frequency bands. Five recordings of 60 min, acquired from three subjects while performing three different mental tasks, were analyzed offline. No artifacts were removed or rejected. We noticed significant differences between PLV and mean spectral coherence. For sole use of synchronization measures, classification accuracies up to 62 percent were achieved. In general, the best result was obtained combining phase synchronization measures with alpha power spectral density estimates. The results demonstrate that phase synchronization provides relevant information for the classification of spontaneous EEG during mental tasks.

PubMed ***Documents from the National Library of Medicine PubMed search at www.pubmed.com are listed below:***

2008

Aloise, F.; Babiloni, F.; Bufalari, S.; Cherubini, A.; Cincotti,F.; Marciani, M.G.; Mattia, D.; Oriolo, G.; & Schalk, G. (2008). **Non-invasive brain-computer interface system: Towards its application as assistive technology.** *Brain Research Bulletin, 75*(6), 796-803.
PMID #: 18394526
ABSTRACT: The quality of life of people suffering from severe motor disabilities can benefit from the use of current assistive technology capable of ameliorating communication, house-environment management and mobility, according to the user's residual motor abilities. BCIs are systems that can translate brain activity into signals that control external devices. Thus they can represent the only technology for severely paralyzed patients to increase or maintain their communication and control options. Here we report on a pilot study in which a system was implemented and validated to allow disabled persons to improve or recover their mobility (directly or by emulation) and communication within the surrounding environment. The system is based on a software controller that offers to the user a communication interface that is matched with the individual's residual motor abilities. Patients (n=14) with severe motor disabilities due to progressive neurodegenerative disorders were trained to use the system prototype under a rehabilitation program carried out in a house-like furnished space. All users utilized regular assistive control options (e.g., microswitches or head trackers). In addition, four subjects learned to operate the system by means of a non-invasive EEG-based BCI. This system was controlled by the subjects' voluntary modulations of EEG sensorimotor rhythms recorded on the scalp; this skill was learnt even though the subjects have not had control over their limbs for a long time. We conclude that such a prototype system, which integrates several different assistive technologies including a BCI system, can potentially facilitate the translation from pre-clinical demonstrations to a clinical useful BCI.

Bai, O.; Floeter, M.K.; Hallett, M.; Hattori, N.; Lin, P.; & Vorbach, S. (2008). **A high performance sensorimotor beta rhythm-based brain-computer interface associated with human natural motor behavior.** *Journal of Neural Engineering, 5*(1), 24-35.
PMID #: 18310808
ABSTRACT: To explore the reliability of a high performance BCI using non-invasive EEG signals associated with human natural motor behavior does not require extensive training. We propose a new BCI method, where users perform either sustaining or stopping a motor task with time locking to a predefined time window. Nine healthy volunteers, one stroke survivor with right-sided hemi-paresis and one patient with amyotrophic lateral sclerosis (ALS) participated in this study. Subjects did not receive BCI training before participating in this study. We investigated tasks of both physical movement and motor imagery. The surface Laplacian derivation was used for enhancing EEG spatial resolution. A model-free threshold setting method was used for the classification of motor intentions. The performance of the proposed BCI was validated by an online sequential binary-cursor-control game for two-dimensional cursor movement. Event-related desynchronization and synchronization were observed when subjects sustained or stopped either motor execution or motor imagery. Feature analysis showed that EEG beta band activity over sensorimotor area provided the largest discrimination. With simple model-free classification of beta band EEG activity from a single electrode (with surface Laplacian derivation), the online classifications of the EEG activity with motor execution/ motor imagery were: greater than 90 percent/ approximately 80 percent for six healthy volunteers, greater than 80 percent/ approximately 80 percent for the stroke patient and approximately 90 percent/ approximately 80 percent for the ALS patient. The EEG activities of the other three healthy volunteers were not classifiable. The sensorimotor beta rhythm of EEG associated with human natural motor behavior can be used for a reliable and high performance BCI for both healthy subjects and patients with neurological disorders. Significance: The proposed new non-invasive BCI method highlights a practical BCI for clinical applications, where the user does not require extensive training.

Diserens, K.; Ebrahimi, T.; Hoffmann, U.; & Vesin, J.M. (2008). **An efficient P300-based brain-computer interface for disabled subjects**. *Journal of Neuroscience Methods, 167*(1), 115-25.
PMID #: 17445904
ABSTRACT: A BCI is a communication system that translates brain-activity into commands for a computer or other devices. In other words, a BCI allows users to act on their environment by using only brain-activity, without using peripheral nerves and muscles. In this paper, we present a BCI that achieves high classification accuracy and high bitrates for both disabled and able-bodied subjects. The system is based on the P300 evoked potential and is tested with five severely disabled and four able-bodied subjects. For four of the disabled subjects classification accuracies of 100 percent are obtained. The bitrates obtained for the disabled subjects range between 10 and 25bits/min. The effect of different electrode configurations and machine learning algorithms on classification accuracy is tested. Further factors that are possibly important for obtaining good classification accuracy in P300-based BCI systems for disabled subjects are discussed.

Itakura, N.; & Yoshimura, N. (2008). **Study on transient VEP-based brain-computer interface using non-direct gazed visual stimuli.** *Electromyography and Clinical Neurophysiology, 48*(1), 43-51.
PMID #: 18338534
ABSTRACT: It is necessary for BCIs to be non-offensive devices for daily use to improve the quality of life of users, especially for the motor disabled. Some BCIs which are based on steady-state visual evoked potentials (SSVEPs), however, are unpleasant because users have to gaze at high-speed blinking light as visual stimuli. Furthermore, these kinds of BCIs may not be used as universal devices because SSVEPs are not detectable by some users. Considering these facts, we propose a novel BCI using a non-direct gazing method based on transient VEPs. This interface uses a low-speed blinking lattice pattern as visual stimuli, and users gaze at other visual targets displayed on the right and the left sides of the stimuli. The gazing direction is determined by the waveform difference of transient VEPs detected when users gaze at either target.
Compared with SSVEP-based BCIs, the proposed BCI is less annoying because it uses a low-speed blinking pattern as visual stimuli and users do not have to gaze at the stimuli directly. In addition, bipolar derivation could reduce unnecessary signals and the number of responses used for signal averaging to detect transient VEPs, which leads to shorter detection time of the VEPs providing this interface with acceptable speed as a BCI in terms of determining gazing direction. Experiments

with 7 volunteer subjects showed more than an 85 percent accuracy rate in gaze direction judgments. The result suggests that the proposed BCI can be used as a substitute for SSVEP-based BCIs, especially for users in which SSVEPs are not detected.

Krusienski, D.J.; McFarlan, D.J.; Sarnacki, W.A.; & Wolpaw, J.R. (2008). **Emulation of computer mouse control with a noninvasive brain-computer interface.** *Journal of Neural Engineering, 5*(2), 101-10.
PMID #: 18367779
ABSTRACT: BCI technology can provide non-muscular communication and control to people who are severely paralyzed. BCIs can use noninvasive or invasive techniques for recording the brain signals that convey the user's commands. Although noninvasive BCIs are used for simple applications, it has frequently been assumed that only invasive BCIs, which use electrodes implanted in the brain, will be able to provide multidimensional sequential control of a robotic arm or a neuroprosthesis. The present study shows that a noninvasive BCI using scalp-recorded electroencephalographic (EEG) activity and an adaptive algorithm can provide people, including people with spinal cord injuries, with two-dimensional cursor movement and target selection. Multiple targets were presented around the periphery of a computer screen, with one designated as the correct target. The user's task was to use EEG to move a cursor from the center of the screen to the correct target and then to use an additional EEG feature to select the target. If the cursor reached an incorrect target, the user was instructed not to select it. Thus, this task emulated the key features of mouse operation. The results indicate that people with severe motor disabilities could use brain signals for sequential multidimensional movement and selection.

2007

Acharya, S.; Aggarwal, V.; Chatterjee, A.; Ramos, A.; & Thakor, N.V. (2007). **A brain-computer interface with vibrotactile biofeedback for haptic information.** *Journal of Neuroengineering and Rehabilitation, 4,* 40.
PMID #: 17941986
ABSTRACT: BACKGROUND: It has been suggested that BCI may one day be suitable for controlling a neuroprosthesis. For closed-loop operation of BCI, a tactile feedback channel that is compatible with neuro-prosthetic applications is desired. Operation of an EEG-based BCI using only vibrotactile feedback, a commonly used method to convey haptic senses of contact and pressure, is demonstrated with a high level of accuracy. METHODS: A Mu-rhythm based BCI using a motor imagery paradigm was used to control the position of a virtual cursor. The cursor position was shown visually as well as transmitted haptically by modulating the intensity of a vibrotactile stimulus to the upper limb. A total of six subjects operated the BCI in a two-stage targeting task, receiving only vibrotactile biofeedback of performance. The location of the vibration was also systematically varied between the left and right arms to investigate location-dependent effects on performance. RESULTS AND CONCLUSION: Subjects are able to control the BCI using only vibrotactile feedback with an average accuracy of 56 percent and as high as 72 percent. These accuracies are significantly higher than the 15 percent predicted by random chance if the subject had no voluntary control of their Mu-rhythm. The results of this study demonstrate that vibrotactile feedback is an effective biofeedback modality to operate a BCI using motor imagery. In addition, the study shows that placement of the vibrotactile stimulation on the biceps ipsilateral or contralateral to the motor imagery introduces a significant bias in the BCI accuracy. This bias is consistent with a drop in performance generated by stimulation of the contralateral limb. Users demonstrated the capability to overcome this bias with training.

Achtman, N.; Afshar, A.; Ryu, S.I.; Santhanam, G.; Shenoy, K.V.; & Yu, B.M. (2007). **Free-paced high-performance brain-computer interfaces.** *Journal of Neural Engineering, 4*(3), 336-47.
PMID #: 17873435
ABSTRACT: Neural prostheses aim to improve the quality of life of severely disabled patients by translating neural activity into control signals for guiding prosthetic devices or computer cursors. We recently demonstrated that plan activity from pre-motor cortex, which specifies the endpoint of the upcoming arm movement, can be used to swiftly and accurately guide computer cursors to the desired target locations. However, these systems currently require additional, non-neural information to specify when plan activity is present. We report here the design and performance of state estimator algorithms for automatically detecting the presence of plan activity using neural activity alone. Prosthesis

performance was nearly as good when state estimation was used as when perfect plan timing information was provided separately (approximately five percentage points lower, when using 200 ms of plan activity). These results strongly suggest that a completely neurally-driven high-performance BCI is possible.

Alaranta, H.; Jylänki, P.; Kauhanen, L.; Lehtonen, J.; Rantanen, P.; & Sams, M. (2007). **EEG-based brain-computer interface for tetraplegics.** *Computational Intelligence and Neuroscience, 2007*, 23864.
PMID #: 18288247
ABSTRACT: Movement-disabled persons typically require a long practice time to learn how to use a BCI. Our aim was to develop a BCI which tetraplegic subjects could control only in 30 minutes. Six such subjects (level of injury C4-C5) operated a six-channel EEG BCI. The task was to move a circle from the centre of the computer screen to its right or left side by attempting visually triggered right- or left-hand movements. During the training periods, the classifier was adapted to the user's EEG activity after each movement attempt in a supervised manner. Feedback of the performance was given immediately after starting the BCI use. Within the time limit, three subjects learned to control the BCI. We believe that fast initial learning is an important factor that increases motivation and willingness to use BCIs. We have previously tested a similar single-trial classification approach in healthy subjects. Our new results show that methods developed and tested with healthy subjects do not necessarily work as well as with motor-disabled patients. Therefore, it is important to use motor-disabled persons as subjects in BCI development.

Allison, B.Z.; Wolpaw, E.W.; & Wolpaw, J.R. (2007). **Brain-computer interface systems: Progress and prospects.** *Expert Review of Medical Devices, 4*(4), 463-74.
PMID #: 17605682
ABSTRACT: BCI systems support communication through direct measures of neural activity without muscle activity. BCIs may provide the best and sometimes the only communication option for users disabled by the most severe neuromuscular disorders and may eventually become useful to less severely disabled and/or healthy individuals across a wide range of applications. This review discusses the structure and functions of BCI systems, clarifies terminology and addresses practical applications. Progress and opportunities in the field are also identified and explicated.

Aloise, F.; Babiloni, F.; Bufalari, S.; Cherubini, A.; Cincotti, F.; Davide, F.; Marciani, M.G.; Mattia, D.; Oriolo, G.; & Schalk, G. (2007). **Non-invasive brain-computer interface system to operate assistive devices.** *Conference proceedings: Annual International Conference of the IEEE Engineering in Medicine and Biology Society. IEEE Engineering in Medicine and Biology Society, 2007*, 2532-5.
PMID #: 18002510
ABSTRACT: In this pilot study, a system that allows disabled persons to improve or recover their mobility and communication within the surrounding environment was implemented and validated. The system is based on a software controller that offers to the user a communication interface that is matched with the individual's residual motor abilities. Fourteen patients with severe motor disabilities due to progressive neurodegenerative disorders were trained to use the system prototype under a rehabilitation program. All users utilized regular assistive control options (e.g., microswitches or head trackers) while four patients learned to operate the system by means of a non-invasive EEG-based BCI, based on the subjects' voluntary modulations of EEG sensorimotor rhythms recorded on the scalp.

Aloise, F.; Babiloni, F.; Caporusso, N.; Cincotti, F.; Del R Millán, J.; Jylänki, P.; Kauhanen, L.; Marciani, M.G.; Mattia, D.; Nuttin, M.; Palomäki, T.; & Vanacker, G. (2007). **Vibrotactile feedback for brain-computer interface operation.** *Computational Intelligence and Neuroscience, 2007*, 48937.
PMID #: 18354734
ABSTRACT: To be correctly mastered, BCIs need an uninterrupted flow of feedback to the user. This feedback is usually delivered through the visual channel. Our aim was to explore the benefits of vibrotactile feedback during users' training and control of EEG-based BCI applications. A protocol for delivering vibrotactile feedback, including specific hardware and software arrangements, was specified. In three studies with 33 subjects (including three with spinal cord injury), we compared vibrotactile and visual feedback, addressing: (1) the feasibility of subjects' training to master their EEG rhythms using tactile feedback; (2) the compatibility of this form of feedback in presence of a visual distracter; (3) the performance in presence of a complex visual task on the same (visual) or different (tactile) sensory channel. The stimulation protocol we developed supports a general usage of the tactors; pre-

liminary experimentations. All studies indicated that the vibrotactile channel can function as a valuable feedback modality with reliability comparable to the classical visual feedback. Advantages of using a vibrotactile feedback emerged when the visual channel was highly loaded by a complex task. In all experiments, vibrotactile feedback felt, after some training, more natural for both controls and SCI users.

Angelakis, E.; Hatzis, A.; Panourias, I.G.; & Sakas, D.E. (2007). **Brain-computer interface: A reciprocal self-regulated neuromodulation.** *Acta Neurochirurgica Supplement, 97*(Pt 2), 555-9.
PMID #: 17691347
ABSTRACT: BCI is a system that records brain activity and process it through a computer, allowing the individual whose activity is recorded to monitor this activity at the same time. Applications of BCIs include assistive modules for severely paralyzed patients to help them control external devices or to communicate, as well as brain biofeedback to self regulate brain activity for treating epilepsy, attention-deficit hyperactivity disorder (ADHD), anxiety, and other psychiatric conditions, or to enhance cognitive performance in healthy individuals. The vast majority of BCIs utilizes non-invasive scalp recorded electroencephalographic (EEG) signals, but other techniques like invasive intracortical EEG, or near-infrared spectroscopy measuring brain blood oxygenation are tried experimentally.

Ard, T.; Birbaumer, N.; Braun, C.; Buch, E.; Caria, A.; Cohen, L.G.; Dimyan, M.A.; Fourkas, A.; Mellinger, J.; Soekadar, S.; & Weber, C. (2007). **Think to move: A neuro-magnetic brain-computer interface (BCI) system for chronic stroke.** *Stroke: A Journal of Cerebral Circulation, 39*(3), 910-7.
PMID #: 18258825
ABSTRACT: BACKGROUND AND PURPOSE: Stroke is a leading cause of long-term motor disability among adults. Present rehabilitative interventions are largely unsuccessful in improving the most severe cases of motor impairment, particularly in relation to hand function. Here we tested the hypothesis that patients experiencing hand plegia as a result of a single, unilateral subcortical, cortical or mixed stroke occurring at least one year previously, could be trained to operate a mechanical hand orthosis through a BCI. METHODS: Eight patients with chronic hand plegia resulting from stroke (residual finger extension function rated on the Medical Research Council scale=0/5) were recruited from the Stroke Neuro-rehabilitation Clinic, Human Cortical Physiology Section of the National Institute for Neurological Disorders and Stroke (NINDS) (n=5) and the Clinic of Neurology of the University of Tübingen (n=3). Diagnostic MRIs revealed single, unilateral subcortical, cortical or mixed lesions in all patients. A magnetoencephalography-based BCI system was used for this study. Patients participated in between 13 to 22 training sessions geared to volitionally modulate micro rhythm amplitude originating in sensorimotor areas of the cortex, which in turn raised or lowered a screen cursor in the direction of a target displayed on the screen through the BCI interface. Performance feedback was provided visually in real-time. Successful trials (in which the cursor made contact with the target) resulted in opening/closing of an orthosis attached to the paralyzed hand. RESULTS: Training resulted in successful BCI control in six of eight patients. This control was associated with increased range and specificity of mu rhythm modulation as recorded from sensors overlying central ipsilesional (four patients) or contralesional (two patients) regions of the array. Clinical scales used to rate hand function showed no significant improvement after training. CONCLUSIONS: These results suggest that volitional control of neuro-magnetic activity features recorded over central scalp regions can be achieved with BCI training after stroke, and used to control grasping actions through a mechanical hand orthosis.

Birbaumer, N.; Braun, C.; Kübler, A.; Mellinger, J.; Preissl, H.; Rosenstiel, W.; & Schalk, G. (2007). **An MEG-based brain-computer interface (BCI).** *NeuroImage, 36*(3), 581-93.
PMID #: 17475511
ABSTRACT: BCIs allow for communicating intentions by mere brain activity, not involving muscles. Thus, BCIs may offer patients who have lost all voluntary muscle control the only possible way to communicate. Many recent studies have demonstrated that BCIs based on electroencephalography (EEG) can allow healthy and severely paralyzed individuals to communicate. While this approach is safe and inexpensive, communication is slow. Magnetoencephalography (MEG) provides signals with higher spatiotemporal resolution than EEG and could thus be used to explore whether these improved signal properties translate into increased BCI communication speed. In this study, we investigated the utility of an MEG-based BCI that uses voluntary amplitude

modulation of sensorimotor mu and beta rhythms. To increase the signal-to-noise ratio, we present a simple spatial filtering method that takes the geometric properties of signal propagation in MEG into account, and we present methods that can process artifacts specifically encountered in an MEG-based BCI. Exemplarily, six participants were successfully trained to communicate binary decisions by imagery of limb movements using a feedback paradigm. Participants achieved significant mu rhythm self control within 32 min of feedback training. For a subgroup of three participants, we localized the origin of the amplitude modulated signal to the motor cortex. Our results suggest that an MEG-based BCI is feasible and efficient in terms of user training.

Birbaumer, N.; Furdea, A.; Gunst, I.; Kübler, A.; McFarland, D.J.; Mellinger, J.; & Nijboer, F. (2007). **An auditory brain-computer interface (BCI).** *Journal of Neuroscience Methods, 167*(1), 43-50.
PMID #: 17399797
ABSTRACT: BCIs translate brain activity into signals controlling external devices. BCIs based on visual stimuli can maintain communication in severely paralyzed patients, but only if intact vision is available. Debilitating neurological disorders however, may lead to loss of intact vision. The current study explores the feasibility of an auditory BCI. Sixteen healthy volunteers participated in three training sessions consisting of 30 2-3 min runs in which they learned to increase or decrease the amplitude of sensorimotor rhythms (SMR) of the EEG. Half of the participants were presented with visual and half with auditory feedback. Mood and motivation were assessed prior to each session. Although BCI performance in the visual feedback group was superior to the auditory feedback group there was no difference in performance at the end of the third session. Participants in the auditory feedback group learned slower, but four out of eight reached an accuracy of over 70 percent correct in the last session comparable to the visual feedback group. Decreasing performance of some participants in the visual feedback group is related to mood and motivation. We conclude that with sufficient training time an auditory BCI may be as efficient as a visual BCI. Mood and motivation play a role in learning to use a BCI.

Blankertz, B.; Curio, G.; Dornhege, G.; Krauledat, M.; & Müller, K.R. (2007). **The non-invasive Berlin Brain-Computer Interface: Fast acquisition of effective performance in untrained subjects.** *NeuroImage, 37*(2), 539-50.
PMID #: 17475513
ABSTRACT: BCI systems establish a direct communication channel from the brain to an output device. These systems use brain signals recorded from the scalp, the surface of the cortex, or from inside the brain to enable users to control a variety of applications. BCI systems that bypass conventional motor output pathways of nerves and muscles can provide novel control options for paralyzed patients. One classical approach to establish EEG-based control is to set up a system that is controlled by a specific EEG feature which is known to be susceptible to conditioning and to let the subjects learn the voluntary control of that feature. In contrast, the Berlin Brain-Computer Interface (BBCI) uses well established motor competencies of its users and a machine learning approach to extract subject-specific patterns from high-dimensional features optimized for detecting the user's intent. Thus the long subject training is replaced by a short calibration measurement (20 min) and machine learning (1 min). We report results from a study in which 10 subjects, who had no or little experience with BCI feedback, controlled computer applications by voluntary imagination of limb movements: these intentions led to modulations of spontaneous brain activity specifically, somatotopically matched sensorimotor 7-30 Hz rhythms were diminished over pericentral cortices. The peak information transfer rate was above 35 bits per minute (bpm) for three subjects, above 23 bpm for two, and above 12 bpm for three subjects, while one subject could achieve no BCI control. Compared to other BCI systems which need longer subject training to achieve comparable results, we propose that the key to quick efficiency in the BBCI system is its flexibility due to complex but physiologically meaningful features and its adaptivity which respects the enormous inter-subject variability.

Dobkin, B.H. (2007). **Brain-computer interface technology as a tool to augment plasticity and outcomes for neurological rehabilitation.** *Journal de Physiologie, 579*(Pt 3), 637-42.
PMID #: 17095557
ABSTRACT: BCIs are a rehabilitation tool for tetraplegic patients that aim to improve quality of life by augmenting communication, control of the environment, and self-care. The neurobiology of both reha-

bilitation and BCI control depends upon learning to modify the efficacy of spared neural ensembles that represent movement, sensation and cognition through progressive practice with feedback and reward. To serve patients, BCI systems must become safe, reliable, cosmetically acceptable, quickly mastered with minimal ongoing technical support, and highly accurate even in the face of mental distractions and the uncontrolled environment beyond a laboratory. BCI technologies may raise ethical concerns if their availability affects the decisions of patients who become locked-in with brain stem stroke or amyotrophic lateral sclerosis to be sustained with ventilator support. If BCI technology becomes flexible and affordable, volitional control of cortical signals could be employed for the rehabilitation of motor and cognitive impairments in hemiplegic or paraplegic patients by offering on-line feedback about cortical activity associated with mental practice, motor intention, and other neural recruitment strategies during progressive task-oriented practice. Clinical trials with measures of quality of life will be necessary to demonstrate the value of near-term and future BCI applications.

Felton, E.A.; Garell, P.C.; Williams, J.C.; & Wilson, J.A. (2007). **Electrocorticographically controlled brain-computer interfaces using motor and sensory imagery in patients with temporary subdural electrode implants. Report of four cases.** *Journal of Neurosurgery, 106*(3), 495-500.
PMID #: 17367076
ABSTRACT: BCI technology can offer individuals with severe motor disabilities greater independence and a higher quality of life. The BCI systems take recorded brain signals and translate them into real-time actions, for improved communication, movement, or perception. Four patient participants with a clinical need for intracranial electrocorticography (ECoG) participated in this study. The participants were trained over multiple sessions to use motor and/or auditory imagery to modulate their brain signals in order to control the movement of a computer cursor. Participants with electrodes over motor and/or sensory areas were able to achieve cursor control over two to seven days of training. These findings indicate that sensory and other brain areas not previously considered ideal for ECoG-based control can provide additional channels of control that may be useful for a motor BCI.

Gao, S.; Gao, X.; Hong, B.; & Wang, Y. (2007). **Implementation of a brain-computer interface based on three states of motor imagery.** *Conference proceedings: Annual International Conference of the IEEE Engineering in Medicine and Biology Society. IEEE Engineering in Medicine and Biology Society, 2007,* 5059-62.
PMID #: 18003143
ABSTRACT: A motor imagery based BCI translates the subject's motor intention into a control signal through real-time detection of characteristic EEG spatial distributions corresponding to motor imagination of different body parts. In this paper, we implemented a three-class BCI manipulated through imagination of left hand, right hand and foot movements, inducing different spatial patterns of event-related desynchronization on mu rhythms over the sensory-motor cortex. A two-step training approach was proposed including consecutive steps of online adaptive training and offline training. Then, the optimized parameters and classifiers were utilized for online control. This paradigm facilitated three directional movement controls which could be easily applied to help the motion-disabled to operate a wheelchair. The average online and offline classification accuracy on five subjects was 79.48 and 85.00 percent respectively, promoting the three-class motor imagery based BCI a promising means to realize brain control of a mobile device.

Karlovskii, D.V.; Konyshev, V.A.; & Selishchev, S.V. (2007). **[A P300-based brain-computer interface].** *Meditsinskaia Tekhnika,* (1), 28-32. *Article in Russian.*
PMID #: 17419343
ABSTRACT: The goal of this work was to describe a system for real-time typing controlled by brain bio-potential signals. A 6 (6 matrix containing Russian alphabet letters and auxiliary symbols was shown on PC screen. Electroencephalogram was taken, and the P300 component was extracted (this component appeared only upon presentation of a significant stimulus). A combination of several detection methods was used to identify the P300 component, which made it possible to increase the probability of correct identification to 91.6 (5.2 percent. It was shown that the developed interface could be implemented on the basis of a single active electrode in Pz (Cz) position.

Kotchoubey, B.; & Kübler, A. (2007). **Brain-computer interfaces in the continuum of consciousness.** *Current Opinion in Neurology, 20*(6), 643-9.
PMID #: 17992083
ABSTRACT: PURPOSE OF REVIEW: To summarize recent developments and look at important future aspects of BCIs. RECENT FINDINGS: Recent BCI studies are largely targeted at helping severely or even completely paralyzed patients. The former are only able to communicate yes or no via a single muscle twitch, and the latter are totally non-responsive. Such patients can control BCIs and use them to select letters, words or items on a computer screen, for neuro-prosthesis control or for surfing the Internet. This condition of motor paralysis, in which cognition and consciousness appear to be unaffected, is traditionally opposed to non-responsiveness due to disorders of consciousness. Although these groups of patients may appear to be very alike, numerous transition states between them are demonstrated by recent studies. SUMMARY: All non-responsive patients can be regarded on a continuum of consciousness which may vary even within short time periods. As overt behavior is lacking, cognitive functions in such patients can only be investigated using neuro-physiological methods. We suggest that BCIs may provide a new tool to investigate cognition in disorders of consciousness, and propose a hierarchical procedure entailing passive stimulation, active instructions, volitional paradigms, and BCI operation.

2006

Bakay, R.A. (2006). **Limits of brain-computer interface: Case report.** *Neurosurgical Focus, 20*(5), E6.
PMID #: 16711663
ABSTRACT: Most patients who are candidates for BCI studies have an injury to their central nervous system and therefore may not be ideal for rigorous testing of the full abilities and limits of the interface. This is a report on a quadriplegic patient who appeared to be a reasonable candidate for intracranial implantation of neuro-trophic electrodes. He had significant cortical atrophy in both the motor and parietal cortical areas but was able to generate signal changes on functional magnetic resonance images by thinking about hand movements. Only a few low-amplitude action potentials were obtained, however, and he was unable to achieve single-unit control. Despite this failure, the use of field potentials offered an alternative method of control and allowed him some limited computer interactions. There are clearly limits to what can be achieved with BCIs, and the presence of cortical atrophy should serve as a warning for future investigators that less invasive techniques may be a more prudent approach for this type of patient.

Barros, A.K.; Cichocki, A.; Funase, A.; Takumi, I.; & Yagi, T. (2006). **Single trial method for brain-computer interface.** *Conference proceedings: Annual International Conference of the IEEE Engineering in Medicine and Biology Society. IEEE Engineering in Medicine and Biology Society, 2006*, 1, 5277-81.
PMID #: 17947135
ABSTRACT: Electroencephalogram (EEG) related to fast eye movement (saccade), has been the subject of application oriented research by our group toward developing a BCI. Our goal is to develop novel BCI based on eye movements system employing EEG signals online. Most of the analysis of the saccade-related EEG data has been performed using ensemble averaging approaches. However, ensemble averaging is not suitable for BCI. In order to process raw EEG data in real time, we performed saccade-related EEG experiments and processed data by using the non-conventional fast ICA with reference signal (FICAR). The FICAR algorithm can extract desired independent components (IC) which have strong correlation against a reference signal. Visually guided saccade tasks and auditory guided saccade tasks were performed and the EEG signal generated in the saccade was recorded. The EEG processing was performed in three stages: PCA preprocessing and noise reduction, extraction of the desired IC using Wiener filter with reference signal, and post-processing using higher order statistics fast ICA based on maximization of kurtosis. Form the experimental results and analysis we found that using FICAR it is possible to extract form raw EEG data the saccade-related ICs and to predict saccade in advance by about 10 [ms] before real movements of eyes occurs. For single trail EEG data we have successfully extracted the desire ICs with recognition rate about 70 percent. In next steps, saccade-related EEG signals and saccade-related ICs in visually and auditory guided saccade task are compared in the point of the latency between starting time of a saccade and time when a saccade-related EEG signal or an IC has maximum value

and in the point of the peak scale where a saccade-related EEG signal or an IC has maximum value. As results, peak time when saccade-related ICs have maximum amplitude is earlier than peak time when saccade-related EEG signals have maximum amplitude. This is very important advantage for developing our CI. However, S/N ratio in being processed by FICAR is not improved comparing S/N ratio in being processed by ensemble averaging.

Birbaumer, N. (2006). **Brain-computer-interface research: Coming of age.** *Clinical Neurophysiology, 117*(3), 479-83.
PMID #: 16458595
No abstract available.

Birbaumer, N.; Buch, E.; Cohen, L.; Haapen, K.; Neuper, C.; & Weber, C. (2006). **Physiological regulation of thinking: Brain-computer interface (BCI) research.** *Progress in Brain Research, 159*, 369-91.
PMID #: 17071243
ABSTRACT: The discovery of event-related desynchronization (ERD) and event-related synchronization (ERS) by Pfurtscheller paved the way for the development of BCIs. BCIs allow control of computers or external devices with the regulation of brain activity only. Two different research traditions produced two different types of BCIs: invasive BCIs, realized with implanted electrodes in brain tissue and noninvasive BCIs using electrophysiological recordings in humans such as electroencephalography (EEG) and magnetoencephalography (MEG) and metabolic changes such as functional magnetic resonance imaging (fMRI) and near infrared spectroscopy (NIRS). Clinical applications were reserved with few exceptions for the noninvasive approach: communication with the completely paralyzed and locked-in syndrome with slow cortical potentials (SCPs), sensorimotor rhythms (SMRs), and P300 and restoration of movement and cortical reorganization in high spinal cord lesions and chronic stroke. It was demonstrated that noninvasive EEG-based BCIs allow brain-derived communication in paralyzed and locked-in patients. Movement restoration was achieved with noninvasive BCIs based on SMRs control in single cases with spinal cord lesions and chronic stroke. At present no firm conclusion about the clinical utility of BCI for the control of voluntary movement can be made. Invasive multielectrode BCIs in otherwise healthy animals allowed execution of reaching, grasping, and force variations from spike patterns and extracellular field potentials. Whether invasive approaches allow superior brain control of motor responses compared to noninvasive BCI with intelligent peripheral devices and electrical muscle stimulation and EMG feedback remains to be demonstrated. The newly developed fMRI-BCIs and NIRS-BCIs offer promise for the learned regulation of emotional disorders and also disorders of small children (in the case of NIRS).

Birbaumer, N.; Flor, H.; Hinterberger, T.; Karim, A.A.; Kübler, A.; Mellinger, J.; Neumann, N.; & Richter, J. (2006). **Neural internet: Web surfing with brain potentials for the completely paralyzed.** *Neurorehabilitation and Neural Repair, 20*(4), 508-15.
PMID #: 17082507
ABSTRACT: Neural Internet is a new technological advancement in BCI research, which enables locked-in patients to operate a Web browser directly with their brain potentials. Neural Internet was successfully tested with a locked-in patient diagnosed with amyotrophic lateral sclerosis rendering him the first paralyzed person to surf the Internet solely by regulating his electrical brain activity. The functioning of Neural Internet and its clinical implications for motor-impaired patients are highlighted.

Beverina, F.; Giorgi, F.; Giove, S.; Palmas, G.; Piccione, F.; Priftis, K.; Silvoni, S.; & Tonin, P. (2006). **P300-based brain computer interface: Reliability and performance in healthy and paralyzed participants.** *Clinical Neurophysiology, 117*(3), 531-7.
PMID #: 16458069
ABSTRACT: OBJECTIVE: This study aimed to describe the use of the P300 event-related potential as a control signal in a brain computer interface (BCI) for healthy and paralyzed participants. METHODS: The experimental device used the P300 wave to control the movement of an object on a graphical interface. Visual stimuli, consisting of four arrows (up, right, down, left) were randomly presented in peripheral positions on the screen. Participants were instructed to recognize only the arrow indicating a specific direction for an object to move. P300 epochs, synchronized with the stimulus, were analyzed on-line via Independent Component Analysis (ICA) with subsequent feature extraction and classification by using a neural network. RESULTS: We tested the reliability and the performance of the system

in real-time. The system needed a short training period to allow task completion and reached good performance. Nonetheless, severely impaired patients had lower performance than healthy participants. CONCLUSIONS: The proposed system is effective for use with healthy participants, whereas further research is needed before it can be used with locked-in syndrome patients. SIGNIFICANCE: The P300-based BCI described can reliably control, in 'real time', the motion of a cursor on a graphical interface, and no time-consuming training is needed in order to test possible applications for motor-impaired patients.

Blankertz, B.; Curio, G.; Dornhege, G.; Krauledat, M.; Kunzmann, V.; Losch, F.; & Müller, K.R. (2006). **The Berlin Brain-Computer Interface: EEG-based communication without subject training.** *IEEE Transactions on Neural Systems and Rehabilitation Engineering, 14*(2), 147-52.
PMID #: 16792281
ABSTRACT: The Berlin Brain-Computer Interface (BBCI) project develops a noninvasive BCI system whose key features are: (1) the use of well-established motor competences as control paradigms, (2) high-dimensional features from 128-channel electroencephalogram (EEG), and (3) advanced machine learning techniques. As reported earlier, our experiments demonstrate that very high information transfer rates can be achieved using the readiness potential (RP) when predicting the laterality of upcoming left- versus right-hand movements in healthy subjects. A more recent study showed that the RP similarily accompanies phantom movements in arm amputees, but the signal strength decreases with longer loss of the limb. In a complementary approach, oscillatory features are used to discriminate imagined movements (left hand versus right hand versus foot). In a recent feedback study with six healthy subjects with no or very little experience with BCI control, three subjects achieved an information transfer rate above 35 bits per minute (bpm), and further two subjects above 24 and 15 bpm, while one subject could not achieve any BCI control. These results are encouraging for an EEG-based BCI system in untrained subjects that is independent of peripheral nervous system activity and does not rely on evoked potentials even when compared to results with very well-trained subjects operating other BCI systems.

Cabrera, A.F.; Do, Nascimento, O.F.; & Nielsen, K.D. (2006). **EEG based BCI-towards a better control: Brain-computer interface research at Aalborg University.** *IEEE Transactions on Neural Systems and Rehabilitation Engineering, 14*(2), 202-4.
PMID #: 16792294
ABSTRACT: This paper summarizes the BCI-related research being conducted at Aalborg University. Namely, an online synchronized BCI system using steady-state visual evoked potentials, and investigations on cortical modulation of movement-related parameters are presented.

Donchin, E..; & Sellers, E.W. (2006). **A P300-based brain-computer interface: Initial tests by ALS patients.** *Clinical Neurophysiology, 117*(3), 538-48.
PMID #: 16461003
ABSTRACT: OBJECTIVE: The current study evaluates the effectiveness of a BCI system that operates by detecting a P300 elicited by one of four randomly presented stimuli (i.e. YES, NO, PASS, END). METHODS: Two groups of participants were tested. The first group included three amyotrophic lateral sclerosis (ALS) patients that varied in degree of disability, but all retained the ability to communicate; the second group included three non-ALS controls. Each participant participated in ten experimental sessions during a period of approximately six weeks. During each run the participant's task was to attend to one stimulus and disregard the other three. Stimuli were presented auditorily, visually, or in both modes. RESULTS: Two of the three ALS patient's classification rates were equal to those achieved by the non-ALS participants. Waveform morphology varied as a function of the presentation mode, but not in a similar pattern for each participant. CONCLUSIONS: The event-related potentials elicited by the target stimuli could be discriminated from the non-target stimuli for the non-ALS and the ALS groups. Future studies will begin to examine online classification. SIGNIFICANCE: The results of offline classification suggest that a P300-based BCI can serve as a non-muscular communication device in both ALS, and non-ALS control groups.

Donoghue, J.P.; Hochberg, L.R.; Kübler, A.; & Mushahwar, V.K. (2006). **BCI Meeting 2005: Workshop on clinical issues and applications.** *IEEE Transactions on Neural Systems and Rehabilitation Engineering, 14*(2), 131-4.
PMID #: 16792277

ABSTRACT: This paper describes the outcome of discussions held during the Third International BCI Meeting at a workshop charged with reviewing and evaluating the current state of and issues relevant to BCI clinical applications. These include potential BCI users, applications, validation, getting BCIs to users, role of government and industry, plasticity, and ethics.

Guan, C.; Huang, A.; Li, Y.; Lian, Y.; Teo, E.; & Zhang, H. (2006). **Media communication center using brain computer interface.** *Conference proceedings: Annual International Conference of the IEEE Engineering in Medicine and Biology Society. IEEE Engineering in Medicine and Biology Society, 2006*, 1, 2954-7.
PMID #: 17946993
ABSTRACT: This paper attempts to make use of BCI in implementing an application called the media communication center for the paralyzed people. The application is based on the event-related potential called P300 to perform button selections on media and communication programs such as the mp3 player, video player, photo gallery and e-book. One of the key issues in such system is the usability. We study how various tasks affect the application operation, in particular, how typical mental activities cause false trigger during the operation of the application. We study the false acceptance rate under the conditions of closing eyes, reading a book, listening to music and watching a video. Data from five subjects is used to obtain the false rejection rate and false acceptance rate of the BCI system. Our study shows that different mental activities show different impacts on the false acceptance performances.

Krusienski, D.J.; McFarland, D.J.; Sarnacki, W.A.; Schalk, G.; Sellers, E.W.; Vaughan, T.M.; & Wolpaw, J.R. (2006). **The Wadsworth BCI Research and Development Program: At home with BCI.** *IEEE Transactions on Neural Systems and Rehabilitation Engineering, 14*(2), 229-33.
PMID #: 16792301
ABSTRACT: The ultimate goal of BCI technology is to provide communication and control capacities to people with severe motor disabilities. BCI research at the Wadsworth Center focuses primarily on noninvasive, electroencephalography-based BCI methods. We have shown that people, including those with severe motor disabilities, can learn to use sensorimotor rhythms (SMRs) to move a cursor rapidly and accurately in one or two dimensions. We have also improved P300-based BCI operation. We are now translating this laboratory-proven BCI technology into a system that can be used by severely disabled people in their homes with minimal ongoing technical oversight. To accomplish this, we have: improved our general-purpose BCI software (BCI2000); improved online adaptation and feature translation for SMR-based BCI operation; improved the accuracy and bandwidth of P300-based BCI operation; reduced the complexity of system hardware and software and begun to evaluate home system use in appropriate users. These developments have resulted in prototype systems for every day use in people's homes.

Leuthardt, E.C.; Moran, D.; Ojemann, J.G.; & Schalk, G. (2006). **The emerging world of motor neuroprosthetics: A neurosurgical perspective.** *Neurosurgery, 59*(1), 1-14; discussion 1-14.
PMID #: 16823294
ABSTRACT: A motor neuro-prosthetic device, or brain computer interface, is a machine that can take some type of signal from the brain and convert that information into overt device control such that it reflects the intentions of the user's brain. In essence, these constructs can decode the electrophysiological signals representing motor intent. With the parallel evolution of neuroscience, engineering, and rapid computing, the era of clinical neuro-prosthetics is approaching as a practical reality for people with severe motor impairment. Patients with such diseases as spinal cord injury, stroke, limb loss, and neuromuscular disorders may benefit through the implantation of these brain computer interfaces that serve to augment their ability to communicate and interact with their environment. In the upcoming years, it will be important for the neurosurgeon to understand what a brain computer interface is, its fundamental principle of operation, and what the salient surgical issues are when considering implantation. We review the current state of the field of motor Neuro-prosthetics research, the early clinical applications, and the essential considerations from a neurosurgical perspective for the future.

Müller-Putz, G.R.; Pfurtscheller, G.; Rupp, R.; & Scherer, R. (2006). **Brain-computer interfaces for control of neuroprostheses: From synchronous to asynchronous mode of operation.** *Biomedizinische Technik, 51*(2), 57-63.
PMID #: 16915766
ABSTRACT: Transferring a BCI from the laboratory environment into real world applications is directly related to the problem of identifying user intentions from brain signals without any additional information in real

time. From the perspective of signal processing, the BCI has to have an un-cued or asynchronous design. Based on the results of two clinical applications, where 'thought' control of neuro-prostheses based on movement imagery in tetraplegic patients with a high spinal cord injury has been established, the general steps from a synchronous or cue-guided BCI to an internally driven asynchronous brain-switch are discussed. The future potential of BCI methods for various control purposes, especially for functional rehabilitation of tetraplegics using neuro-prosthetics, is outlined.

Nasrabadi, A.M.; Rezaei, S.; Setarehdan, S.K.; & Tavakolian, K. (2006). **Different classification techniques considering brain computer interface applications.** *Journal of Neural Engineering, 3*(2), 139-44.
PMID #: 16705270
ABSTRACT: In this work the application of different machine learning techniques for classification of mental tasks from electroencephalograph (EEG) signals is investigated. The main application for this research is the improvement of BCI systems. For this purpose, Bayesian graphical network, neural network, Bayesian quadratic, Fisher linear and hidden Markov model classifiers are applied to two known EEG datasets in the BCI field. The Bayesian network classifier is used for the first time in this work for classification of EEG signals. The Bayesian network appeared to have a significant accuracy and more consistent classification compared to the other four methods. In addition to classical correct classification accuracy criteria, the mutual information is also used to compare the classification results with other BCI groups.

Wolpaw, J.R.; & Vaughan, T.M. (2006). **The Third International Meeting on Brain-Computer Interface Technology: Making a difference.** *IEEE Transactions on Neural Systems and Rehabilitation Engineering, 14*(2), 126-7.
PMID #: 16792275
ABSTRACT: This special issue of the IEEE Transactions on Neural Systems and Rehabilitation Engineering provides a representative and comprehensive bird's-eye view of the most recent developments in BCI technology from laboratories around the world. The 30 research communications and papers are the direct outcome of the Third International Meeting on Brain-Computer Interface Technology held at the Rensselaerville Institute, Rensselaerville, NY, in June 2005. Fifty-three research groups from North and South America, Europe, and Asia, representing the majority of all the existing BCI laboratories around the world, participated in this highly focused meeting sponsored by the National Institutes of Health and organized by the BCI Laboratory of the Wadsworth Center of the New York State Department of Health. As demonstrated by the papers in this special issue, the rapid advances in BCI research and development make this technology capable of providing communication and control to people severely disabled by amyotrophic lateral sclerosis (ALS), brainstem stroke, cerebral palsy, and other neuromuscular disorders. Future work is expected to improve the performance and utility of BCIs, and to focus increasingly on making them a viable, practical, and affordable communication alternative for many thousands of severely disabled people worldwide.

2005

Birbaumer, N.; Hinterberger, T.; Vatine, J.J.; Veit, R.; Weiskopf, N.; & Wilhelm, B. (2005). **Neuronal mechanisms underlying control of a brain-computer interface.** *The European Journal of Neuroscience, 21*(11), 3169-81.
PMID #: 15978025
ABSTRACT: BCIs enable humans or animals to communicate or control external devices without muscle activity using electric brain signals. The BCI used here is based on self-regulation of slow cortical potentials (SCPs), a skill that most people and paralyzed patients can acquire with training periods of several hours up to months. The neuro-physiological mechanisms and anatomical sources of SCPs and other event-related brain potentials have been described but the neural mechanisms underlying the self-regulation skill for the use of a BCI are unknown. To uncover the relevant areas of brain activation during regulation of SCPs, the BCI was combined with functional magnetic resonance imaging. The electroencephalogram was recorded inside the magnetic resonance imaging scanner in 12 healthy participants who learned to regulate their SCP with feedback and reinforcement. The results demonstrate activation of specific brain areas during execution of the brain regulation skill allowing a person to activate an external device; a successful positive SCP shift compared with a negative shift was closely related to an increase of the blood oxygen level-dependent response

in the basal ganglia. Successful negativity was related to an increased blood oxygen level-dependent response in the thalamus compared with successful positivity. These results may indicate learned regulation of a cortico-striatal-thalamic loop modulating local excitation thresholds of cortical assemblies. The data support the assumption that human subjects learn the regulation of cortical excitation thresholds of large neuronal assemblies as a prerequisite for direct brain communication using an SCP-driven BCI. This skill depends critically on an intact and flexible interaction between the cortico-basal ganglia-thalamic circuits.

Birbaumer, N.; Kübler, A.; McFarland ,D.J.; Mellinger, J.; Nijboer, F.; Pawelzik, H.; Schalk, G.; Vaughan, T.M.; & Wolpaw, J.R. (2005). **Patients with ALS can use sensorimotor rhythms to operate a brain-computer interface.** *Neurology, 64*(10), 1775-7.
PMID #: 15911809
ABSTRACT: People with severe motor disabilities can maintain an acceptable quality of life if they can communicate. BCIs, which do not depend on muscle control, can provide communication. Four people severely disabled by ALS learned to operate a BCI with EEG rhythms recorded over sensorimotor cortex. These results suggest that a sensorimotor rhythm-based BCI could help maintain quality of life for people with ALS.

Edlinger, G.; & Guger, C. (2005). **Laboratory PC and mobile pocket pc brain-computer interface architectures.** *Conference proceedings: Annual International Conference of the IEEE Engineering in Medicine and Biology Society. IEEE Engineering in Medicine and Biology Society, 5*, 5347-50.
PMID #: 17281459
ABSTRACT: EEG-based BCI systems convert brain activity into control signals and have been developed for people with severe disabilities to improve their quality of life. A BCI system has to satisfy different demands depending on the application area. A laboratory PC based system allows the flexible design of multiple/single channel feature extraction, classification methods and experimental paradigms. The key advantage of a Pocket PC based BCI approach is its small dimension and battery supply. Hence a mobile BCI system e.g. mounted on a wheelchair can be realized. This study compares and discusses thoroughly the two mentioned approaches.

Guan, C.; Wang, C.; & Zhang, H. (2005). **P300 brain-computer interface design for communication and control applications.** *Conference proceedings: Annual International Conference of the IEEE Engineering in Medicine and Biology Society. IEEE Engineering in Medicine and Biology Society, 2005*, 5, 5400-3.
PMID #: 17281473
ABSTRACT: This paper introduces the design of a P300-based BCI system. Based on this system, two applications are implemented: a word speller and a remote control device, which are to assist physically disabled people to communicate and control. A number of specific implementation techniques are proposed to achieve good performance in terms of accuracy and reliability. The word speller can achieve a spelling rate of up to 4-6 letters per minute, while both applications achieve 99 percent accuracy in our experiments with healthy subjects.

Inbar, G.F.; Serby, H.; & Yom-Tov, E. (2005). **An improved P300-based brain-computer interface.** *IEEE Transactions on Neural Systems and Rehabilitation Engineering, 13*(1), 89-98.
PMID #: 15813410
ABSTRACT: A BCI is a system for direct communication between brain and computer. The BCI developed in this work is based on a BCI described by Farwell and Donchin in 1988, which allows a subject to communicate one of 36 symbols presented on a 6 x 6 matrix. The system exploits the P300 component of event-related brain potentials (ERP) as a medium for communication. The processing methods distinguish this work from Donchin's work. In this work, independent component analysis (ICA) was used to separate the P300 source from the background noise. A matched filter was used together with averaging and threshold techniques for detecting the existence of P300s. The processing method was evaluated offline on data recorded from six healthy subjects. The method achieved a communication rate of 5.45 symbols/min with an accuracy of 92.1 percent compared to 4.8 symbols/min with an accuracy of 90 percent in Donchin's work. The online interface was tested with the same six subjects. The average communication rate achieved was 4.5 symbols/min with an accuracy of 79.5 percent as apposed to the 4.8 symbols/min with an accuracy of 56 percent in Donchin's work. The presented BCI achieves excellent performance compared to other existing BCIs, and allows a reasonable communication rate, while maintaining a low error rate.

Müller-Putz, G.R.; Pfurtscheller, G.; Rupp, R.; & Scherer, R. (2005). **EEG-based neuroprosthesis control: A step towards clinical practice.** *Neuroscience Letters, 382*(1-2), 169-74.
PMID #: 15911143
ABSTRACT: This case study demonstrates the coupling of an electroencephalogram (EEG)-based BCI with an implanted neuro-prosthesis (Freehand system). Because the patient was available for only three days, the goal was to demonstrate the possibility of a patient gaining control over the motor imagery-based Graz BCI system within a very short training period. By applying himself to an organized and coordinated training procedure, the patient was able to generate distinctive EEG-patterns by the imagination of movements of his paralyzed left hand. These patterns consisted of power decreases in specific frequency bands that could be classified by the BCI. The output signal of the BCI emulated the shoulder joystick usually used, and by consecutive imaginations the patient was able to switch between different grasp phases of the lateral grasp that the Freehand system provided. By performing a part of the grasp-release test, the patient was able to move a simple object from one place to another. The results presented in this work give evidence that BCIs are an option for the control of neuro-prostheses in patients with high spinal cord lesions. The fact that the user learned to control the BCI in a comparatively short time indicates that this method may also be an alternative approach for clinical purposes.

2004

Birbaumer, N.; Flor, H.; Grether, A.; Hinterberger, T.; Hofmayer, N.; Kübler, A.; Neumann, N.; Pham, M.; & Wilhelm, B. (2004). **A multimodal brain-based feedback and communication system.** *Experimental Brain Research, 154*(4), 521-6.
PMID #: 14648013
ABSTRACT: The Thought Translation Device (TTD) is a BCI based on the self-regulation of slow cortical potentials (SCPs) and enables completely paralyzed patients to communicate using their brain potentials. Here, an extended version of the TTD is presented that has an auditory and a combined visual and auditory feedback modality added to the standard visual feedback. This feature is necessary for locked-in patients who are no longer able to focus their gaze. In order to test performance of physiological regulation with auditory feedback 54 healthy participants were randomly assigned to visual, auditory or combined visual-auditory feedback of slow cortical potentials. The training consisted of three sessions with 500 trials per session with random assignment of required cortical positivity or negativity in half of the trials. The data show that physiological regulation of SCPs can be learned with auditory and combined auditory and visual feedback although the performance of auditory feedback alone was significantly worse than with visual feedback alone.

Birbaumer, N.; Hinterberger, T.; McFarland, D.J.; Schalk, G.; & Wolpaw, J.R. (2004). **BCI2000: A general-purpose brain-computer interface (BCI) system.** *IEEE Transactions on Bio-Medical Engineering, 51*(6), 1034-43.
PMID #: 15188875
ABSTRACT: Many laboratories have begun to develop BCI systems that provide communication and control capabilities to people with severe motor disabilities. Further progress and realization of practical applications depends on systematic evaluations and comparisons of different brain signals, recording methods, processing algorithms, output formats, and operating protocols. However, the typical BCI system is designed specifically for one particular BCI method and is, therefore, not suited to the systematic studies that are essential for continued progress. In response to this problem, we have developed a documented general-purpose BCI research and development platform called BCI2000. BCI2000 can incorporate alone or in combination any brain signals, signal processing methods, output devices, and operating protocols. This report is intended to describe to investigators, biomedical engineers, and computer scientists the concepts that the BCI2000 system is based upon and gives examples of successful BCI implementations using this system. To date, we have used BCI2000 to create BCI systems for a variety of brain signals, processing methods, and applications. The data show that these systems function well in online operation and that BCI2000 satisfies the stringent real-time requirements of BCI systems. By substantially reducing labor and cost, BCI2000 facilitates the implementation of different BCI systems and other psycho-physiological experiments. It is available with full documentation and free of charge for research or educational purposes and is currently being used in a variety of studies by many research groups.

Blanchard, G.; & Blankertz, B. (2004). **BCI Competition 2003—Data set IIa: Spatial patterns of self-controlled brain rhythm modulations.** *IEEE Transactions on Bio-Medical Engineering, 51*(6):1062-6.
PMID #: 15188879
ABSTRACT: A BCI is a system that should in its ultimate form translate a subject's intent into a technical control signal without resorting to the classical neuromuscular communication channels. By using that signal to, e.g., control a wheelchair or a neuro-prosthesis, a BCI could become a valuable tool for paralyzed patients. One approach to implement a BCI is to let users learn to self-control the amplitude of some of their brain rhythms as extracted from multi-channel electroencephalogram. We present a method that estimates subject-specific spatial filters which allow for a robust extraction of the rhythm modulations. The effectiveness of the method was proved by achieving the minimum prediction error on data set IIa in the BCI Competition 2003, which consisted of data from three subjects recorded in ten sessions.

Blankertz, B.; Curio, G.; Dornhege, G.; Krauledat, M.; Losch, F.; & Müller, K.R. (2004). **Improving speed and accuracy of brain-computer interfaces using readiness potential features.** *Conference proceedings: Annual International Conference of the IEEE Engineering in Medicine and Biology Society. IEEE Engineering in Medicine and Biology Society, 6*, 4511-5.
PMID #: 17271309
ABSTRACT: To enhance human interaction with machines, research interest is growing to develop a 'BCI', which allows communication of a human with a machine only by use of brain signals. So far, the applicability of such an interface is strongly limited by low bit-transfer rates, slow response times and long training sessions for the subject. The Berlin Brain-Computer Interface (BBCI) project is guided by the idea to train a computer by advanced machine learning techniques both to improve classification performance and to reduce the need of subject training. In this paper we present two directions in which brain-computer interfacing can be enhanced by exploiting the lateralized readiness potential: (1) for establishing a rapid response BCI system that can predict the laterality of upcoming finger movements before EMG onset even in time critical contexts, and (2) to improve information transfer rates in the common BCI approach relying on imagined limb movements.

Curran, E.; Johnsrude, I.; Owen, A.M.; Penny, W.; Stokes, M.; Roberts, S.J.; & Sykacek, P. (2004). **Cognitive tasks for driving a brain-computer interfacing system: A pilot study.** *IEEE Transactions on Neural Systems and Rehabilitation Engineering, 12*(1), 48-54.
PMID #: 15068187
ABSTRACT: Different cognitive tasks were investigated for use with a BCI. The main aim was to evaluate which two of several candidate tasks lead to patterns of electroencephalographic (EEG) activity that could be differentiated most reliably and, therefore, produce the highest communication rate. An optimal signal processing method was also sought to enhance differentiation of EEG profiles across tasks. In ten normal subjects (five male), aged 29-54 years, EEG activity was recorded from four channels during cognitive tasks grouped in pairs, and performed alternately. Four imagery tasks were: spatial navigation around a familiar environment; auditory imagery of a familiar tune; and right and left motor imagery of opening and closing the hand. Signal processing methodology included autoregressive (AR) modeling and classification based on logistic regression and a nonlinear generative classifier. The highest communication rate was found using the navigation and auditory imagery tasks. In terms of classification performance and, hence, possible communication rate, these results were significantly better ($p < 0.05$) than those obtained with the classical pairing of motor tasks involving imaginary movements of the left and right hands. In terms of EEG data analysis, a nonlinear classification model provided more robust results than a linear model ($p << 0.01$), and a lower AR model order than those used in previous work was found to be effective. These findings have implications for establishing appropriate methods to operate BCI systems, particularly for disabled people who may experience difficulty with motor tasks, even motor imagery.

Donoghue, J.P.; Fellows, M.R.; Friehs, G.M.; Ojakangas, C.L.; & Zerris, V.A. (2004). **Brain-machine and brain-computer interfaces.** *Stroke: A Journal of Cerebral Circulation, 35*(11 Suppl 1), 2702-5.
PMID #: 15486335
ABSTRACT: The idea of connecting the human brain to a computer or machine directly is not novel and its potential has been explored in science fiction. With the rapid advances in the areas of information technology, miniaturization and neurosciences there has been a surge of interest in turning fiction into reality. In this paper the

authors review the current state-of-the-art of brain-computer and brain-machine interfaces including neuro-prostheses. The general principles and requirements to produce a successful connection between human and artificial intelligence are outlined and the authors' preliminary experience with a prototype BCI is reported.

Ebrahimi, T.; Garcia, G.; Hoffmann, U.; & Vesin, J.M. (2004). **Application of the evidence framework to brain-computer interfaces.** *Conference proceedings: Annual International Conference of the IEEE Engineering in Medicine and Biology Society. IEEE Engineering in Medicine and Biology Society, 1*, 446-9.
PMID #: 17271709
ABSTRACT: A BCI is a communication system that implements the principle of "think and make it happen without any physical effort". This means a BCI allows a user to act on his environment only by using his thoughts, without using peripheral nerves and muscles. Nearly all BCIs contain as a core part a machine learning algorithm, which learns from training data a function that can be used to discriminate different brain activities. In the present work we use a Bayesian framework for machine learning, the evidence framework [1], [2] to develop a variant of linear discriminant analysis for the use in a BCI based on electroencephalographic measurements (EEG). Properties of the resulting algorithm are: (1) a continuous probabilistic output is given, (2) fast estimation of regularization constants, and (3) the possibility to select among different feature sets, the one which is most promising for classification. The algorithm has been tested on one dataset from the BCI competition 2002 and two datasets from the BCI competition 2003 and provides a classification accuracy of 95, 81, and 79 percent respectively.

Leuthardt, E.C.; Moran, D.W.; Ojemann, J.G.; Schalk, G.; & Wolpaw, J.R. (2004**). A brain-computer interface using electrocorticographic signals in humans.** *Journal of Neural Engineering, 1*(2), 63-71.
PMID #: 15876624
ABSTRACT: BCIs enable users to control devices with electroencephalographic (EEG) activity from the scalp or with single-neuron activity from within the brain. Both methods have disadvantages: EEG has limited resolution and requires extensive training, while single-neuron recording entails significant clinical risks and has limited stability. We demonstrate here for the first time that electrocorticographic (ECoG) activity recorded from the surface of the brain can enable users to control a one-dimensional computer cursor rapidly and accurately. We first identified ECoG signals that were associated with different types of motor and speech imagery. Over brief training periods of 3-24 min, four patients then used these signals to master closed-loop control and to achieve success rates of 74-100 percent in a one-dimensional binary task. In additional open-loop experiments, we found that ECoG signals at frequencies up to 180 Hz encoded substantial information about the direction of two-dimensional joystick movements. Our results suggest that an ECoG-based BCI could provide for people with severe motor disabilities a non-muscular communication and control option that is more powerful than EEG-based BCIs and is potentially more stable and less traumatic than BCIs that use electrodes penetrating the brain.

McFarland, D.J.; & Wolpaw, J.R. (2004). **Control of a two-dimensional movement signal by a noninvasive brain-computer interface in humans.** *Proceedings of the National Academy of Sciences of the United States of America, 101*(51), 17849-54.
PMID #: 15585584
ABSTRACT: BCIs can provide communication and control to people who are totally paralyzed. BCIs can use noninvasive or invasive methods for recording the brain signals that convey the user's commands. Whereas noninvasive BCIs are already in use for simple applications, it has been widely assumed that only invasive BCIs, which use electrodes implanted in the brain, can provide multidimensional movement control of a robotic arm or a neuro-prosthesis. We now show that a noninvasive BCI that uses scalp-recorded electroencephalographic activity and an adaptive algorithm can provide humans, including people with spinal cord injuries, with multidimensional point-to-point movement control that falls within the range of that reported with invasive methods in monkeys. In movement time, precision, and accuracy, the results are comparable to those with invasive BCIs. The adaptive algorithm used in this non-invasive BCI identifies and focuses on the electroencephalographic features that the person is best able to control and encourages further improvement in that control. The results suggest that people with severe motor disabilities could use brain signals to operate a robotic arm or a neuro-prosthesis without needing to have electrodes implanted in their brains.

Morris, K. (2004). **Mind moves onscreen: Brain-computer interface comes to trial.** *Lancet Neurology, 3*(6), 329.
PMID #: 15176409
No abstract available.

Ostrosky-Solís, F.; Ramírez, M.; & Santana, D. (2004). **[Recent advances in rehabilitation technology: A review of the brain-computer interface].** *Revista de Neurologia, 39*(5), 447-50. *Article in Spanish.*
PMID #: 15378459
ABSTRACT: INTRODUCTION AND AIMS: In this work we review some of the options available in rehabilitation technology that are used to aid people with severe neuromuscular disorders, and which take electrophysiological activity as a source of biological signals with which to design interfaces. DEVELOPMENT: A number of different researchers have generated a novel communication and control system that utilizes the electrical activity of the brain as a signal that represents the messages or commands an individual sends to the outside world, without using the normal output pathways of the brain, such as peripheral nerves and muscles; instead, this is achieved through an artificial system that extracts, encodes and applies them, called a BCI. The electrophysiological activity for a BCI can be obtained by means of superficial or implanted electrodes, and may therefore be classified as invasive or non-invasive. Five types of brain signals have been explored for use with a BCI: visual evoked potentials, slow cortical potentials, cortical neuronal activity, beta and mu rhythms, and event-related potentials. CONCLUSIONS: Thanks to recent improvements and developments in prototypes, this technology is sure to open up new possibilities of communication and control for the affected population; it also represents a valuable field of multidisciplinary research with numerous interesting applications in areas beyond the sphere of health care.

Tian, M.; Yang, K.; Zhang, H.; Zhao, Y. (2004). **[Advance in brain-computer interface technology].** Journal of Biomedical Engineering, *21*(6),1024-7. *Article in Chinese.*
PMID #: 15646357
ABSTRACT: This paper introduces one of the young, energetic and rapidly growing research fields in biomedical engineering-BCI technology, which can provide augmentative communication and control capabilities to patients with severe motor disabilities. We summarize the first two international meetings for BCI, and present the most typical research fruits. The problems in current studies and the direction for future investigation are analyzed.

Wickelgren, I. (2004). **Neuroprosthetics: Brain-computer interface adds a new dimension.** *Science, 306*(5703), 1878-9.
PMID #: 15591175
No abstract is available.

2003

Adams, K.D.; & Kennedy, P.R. (2003). **A decision tree for brain-computer interface devices.** *IEEE Transactions on Neural Systems and Rehabilitation Engineering, 11*(2), 148-50.
PMID #: 12899259
ABSTRACT: This paper is a first attempt to present a “decision tree” to assist in choosing a BCI device for patients who are nearly or completely “locked-in” (cognitively intact but unable to move or communicate.) The first step is to assess any remaining function. There are six inflexion points in the decision-making process. These depend on the functional status of the patient: (1) some residual movement; (2) no movement, but some residual electromyographic (EMG) activity; (3) fully locked-in with no EMG activity or movements but with conjugate eye movements; (4) same as three but with disconjugate eye movements; (5) same as four but with inadequate assistance from the available EEG-based systems; (6) same as five and accepting of an invasive system.

Birbaumer, N.; Dobkin, B.H.; Donchin, E.; Heetderks, W.J.; Kübler, A.; Moore, M.M.; Rymer, W.Z.; Trejo, .J.; Vaughan, T.M.; Weinrich, M.; Wolpaw, E.W.; & Wolpaw, J.R. (2003). **Brain-computer interface technology: A review of the Second International Meeting.** *IEEE Transactions on Neural Systems and Rehabilitation Engineering, 11*(2), 94-109.
PMID #: 12899247
ABSTRACT: This paper summarizes the BCIs for Communication and Control, The Second International Meeting, held in Rensselaerville, NY, in June 2002. Sponsored by the National Institutes of Health and organized by the Wadsworth Center of the New York State Department of Health, the meeting addressed current work and future plans in BCI research. Ninety-two re-

searchers representing 38 different research groups from the United States, Canada, Europe, and China participated. The BCIs discussed at the meeting use electroencephalographic activity recorded from the scalp or single-neuron activity recorded within cortex to control cursor movement, select letters or icons, or operate neuro-prostheses. The central element in each BCI is a translation algorithm that converts electrophysiological input from the user into output that controls external devices. BCI operation depends on effective interaction between two adaptive controllers, the user who encodes his or her commands in the electrophysiological input provided to the BCI, and the BCI that recognizes the commands contained in the input and expresses them in device control. Current BCIs have maximum information transfer rates of up to 25 b/min. Achievement of greater speed and accuracy requires improvements in signal acquisition and processing, in translation algorithms, and in user training. These improvements depend on interdisciplinary cooperation among neuroscientists, engineers, computer programmers, psychologists, and rehabilitation specialists, and on adoption and widespread application of objective criteria for evaluating alternative methods. The practical use of BCI technology will be determined by the development of appropriate applications and identification of appropriate user groups, and will require careful attention to the needs and desires of individual users.

Birbaumer, N.; Hinterberger, T.; Kaiser, J.; Kübler, A.; & Neumann, N. (2003). **A brain-computer interface (BCI) for the locked-in: Comparison of different EEG classifications for the Thought Translation Device.** *Clinical Neurophysiology, 114*(3), 416-25.
PMID #: 12705422
ABSTRACT: OBJECTIVE: The Thought Translation Device (TTD) for brain-computer interaction was developed to enable totally paralyzed patients to communicate. Patients learn to regulate slow cortical potentials (SCPs) voluntarily with feedback training to select letters. This study reports the comparison of different methods of electroencephalographic (EEG) analysis to improve spelling accuracy with the TTD on a data set of 6,650 trials of a severely paralyzed patient. METHODS: Selections of letters occurred by exceeding a certain SCP amplitude threshold. To enhance the patient's control of an additional event-related cortical potential, a filter with two filter characteristics ('mixed filter') was developed and applied on-line. To improve performance off-line the criterion for threshold-related decisions was varied. Different types of discriminant analysis were applied to the EEG data set as well as on wavelet transformed EEG data. RESULTS: The mixed filter condition increased the patients' performance on-line compared to the SCP filter alone. A threshold, based on the ratio between required selections and rejections, resulted in a further improvement off-line. Discriminant analysis of both time-series SCP data and wavelet transformed data increased the patient's correct response rate off-line. CONCLUSIONS: It is possible to communicate with event-related potentials using the mixed filter feedback method. As wavelet transformed data cannot be fed back on-line before the end of a trial, they are applicable only if immediate feedback is not necessary for a BCI. For future BCIs, wavelet transformed data should serve for BCIs without immediate feedback. A stepwise wavelet transformation would even allow immediate feedback.

Birbaumer, N.; Kübler, A.; Müller, G.R.; Neuper, C.; & Pfurtscheller, G. (2003). **Clinical application of an EEG-based brain-computer interface: A case study in a patient with severe motor impairment.** *Clinical Neurophysiology, 114*(3):399-409.
PMID #: 12705420
ABSTRACT: OBJECTIVE: This case study describes how a completely paralyzed patient, diagnosed with severe cerebral palsy, was trained over a period of several months to use an electroencephalography (EEG)-based BCI for verbal communication. METHODS: EEG feedback training was performed in the patient's home (clinic), supervised from a distant laboratory with the help of a 'telemonitoring system'. Online feedback computation was based on single-trial analysis and classification of specific band power features of the spontaneous EEG. Task-related changes in brain oscillations over the course of training steps was investigated by quantifying time-frequency maps of event-related (de-)synchronization (ERD/ERS). RESULTS: The patient learned to 'produce' two distinct EEG patterns, beta band ERD during movement imagery vs. no ERD during relaxing, and to use this for BCI-controlled spelling. Significant learning progress was found as a function of training session, resulting in an average accuracy level of 70 percent (correct responses) for letter selection. 'Copy spelling' was performed with a rate of approximately one letter per min. CONCLUSIONS: The

proposed BCI training procedure, based on electroencephalogram (EEG) biofeedback and concomitant adaptation of feature extraction and classification, may improve actual levels of communication ability in locked-in patients. 'Telemonitoring-assisted' BCI training facilitates clinical application in a larger number of patients.

Birbaumer, N.; Kübler, A.; Müller, G.R.; Neuper, C.; Pfurtscheller, G.; Skliris, D.; & Staiger-Sälzer, P. (2003). **[EEG-based communication—a new concept for rehabilitative support in patients with severe motor impairment].** *Die Rehabilitation, 42*(6), 371-7. *Article in German.*
PMID #: 14677109
ABSTRACT: This paper describes a paralyzed patient diagnosed with severe infantile cerebral palsy, trained over a period of several months to use an EEG-based BCI for verbal communication. The patient learned to "produce" two distinct EEG patterns by mental imagery and to use this skill for BCI-controlled spelling. The EEG feedback training was conducted at a clinic for Assisted Communications, supervised from a distant laboratory with the help of a telemonitoring system. As a function of training sessions significant learning progress was found, resulting in an average accuracy level of 70 percent correct responses for letter selection. At present, "copy spelling" can be performed with a rate of approximately one letter per minute. The proposed communication device, the "Virtual Keyboard", may improve actual levels of communication ability in completely paralyzed patients. "Telemonitoring-assisted" training facilitates clinical application in a larger number of patients.

Birch, G.E.; Borisoff, J.F.; & Mason, S.G. (2003). **Current trends in brain-computer interface research at the Neil Squire Foundation.** *IEEE Transactions on Neural Systems and Rehabilitation Engineering, 11*(2), 123-6.
PMID #: 12899252
ABSTRACT: The Neil Squire Foundation (NSF) is a Canadian nonprofit organization whose purpose is to create opportunities for independence for individuals who have significant physical disabilities. Over the last ten years, our team in partnership with researchers at the Electrical and Computer Engineering Department, the University of British Columbia, has been working to develop a direct brain-controlled switch for individuals with significant physical disabilities. The NSF Brain Interface Project primarily focuses on the development of BCI switch technologies for intermittent (or asynchronous) control in natural environments. That is, technologies that will work when the User intends control but also remains in a stable off state when there is no intent to control. A prototype of such a switch has successfully been developed. This switch has demonstrated classification accuracies greater than 94 percent. The initial results are promising, but further research is required to improve switch accuracies and reliability and to test these switch technologies over a larger population of users and operating conditions. This paper provides an overview of the NSF brain-switch technologies and details our approach to future work in this area.

Birch, G.E.; & Mason, S.G. (2003). **A general framework for brain-computer interface design.** *IEEE Transactions on Neural Systems and Rehabilitation Engineering, 11*(1), 70-85.
PMID #: 12797728
ABSTRACT: The BCI research community has acknowledged that researchers are experiencing difficulties when they try to compare the BCI techniques described in the literature. In response to this situation, the community has stressed the need for objective methods to compare BCI technologies. Suggested improvements have included the development and use of benchmark applications and standard data sets. However, as a young, multidisciplinary research field, the BCI community lacks a common vocabulary. As a result, this deficiency leads to poor inter-group communication, which hinders the development of the desired methods of comparison. One of the principle reasons for the lack of common vocabulary is the absence of a common functional model of a BCI System. This paper proposes a new functional model for BCI System design. The model supports many features that facilitate the comparison of BCI technologies with other BCI and non-BCI user interface technologies. From this model, taxonomy for BCI System design is developed. Together the model and taxonomy are considered a general framework for BCI System design. The representational power of the proposed framework was evaluated by applying it to a set of existing BCI technologies. The framework could effectively describe all of the BCI System designs tested.

Cheng, M.; Gao, S.; Gao, X.; & Xu, D. (2003). **A BCI-based environmental controller for the motion-disabled.** *IEEE Transactions on Neural Systems and Rehabilitation Engineering, 11*(2), 137-40.
PMID #: 12899256
ABSTRACT: With the development of BCI technology, researchers are now attempting to put current BCI techniques into practical application. This paper presents an environmental controller using a BCI technique based on steady-state visual evoked potential. The system is composed of a stimulator, a digital signal processor, and a trainable infrared remote-controller. The attractive features of this system include noninvasive signal recording, little training requirement, and a high information transfer rate. Our test results have shown that this system can distinguish at least 48 targets and provide a transfer rate up to 68 b/min. The system has been applied to the control of an electric apparatus successfully.

Curran, E.; Gibbs, M.; Pickup, L.; Roberts, S.; Stokes, M.; & Sykacek, P. (2003). **Probabilistic methods in BCI research.** *IEEE Transactions on Neural Systems and Rehabilitation Engineering, 11*(2), 192-5.
PMID #: 12899272
ABSTRACT: This paper suggests a probabilistic treatment of the signal processing part of a BCI. We suggest two improvements for BCIs that cannot be obtained easily with other data driven approaches. Simply by using one large joint distribution as a model of the entire signal processing part of the BCI, we can obtain predictions that implicitly weight information according to its certainty. Offline experiments reveal that this results in statistically significant higher bit rates. Probabilistic methods are also very useful to obtain adaptive learning algorithms that can cope with non-stationary problems. An experimental evaluation shows that an adaptive BCI outperforms the equivalent static implementations, even when using only a moderate number of trials. This suggests that adaptive translation algorithms might help in cases where brain dynamics change due to learning effects or fatigue.

Edlinger, G.; Guger, C.; Harkam, W.; Niedermayer, I.; & Pfurtscheller, G. (2003). **How many people are able to operate an EEG-based brain-computer interface (BCI)?** *IEEE Transactions on Neural Systems and Rehabilitation Engineering, 11*(2), 145-7.
PMID #: 12899258
ABSTRACT: Ninety-nine healthy people participated in a BCI field study conducted at an exposition held in Graz, Austria. Each subject spent 20-30 min on a two-session BCI investigation. The first session consisted of 40 trials conducted without feedback. Then, a subject-specific classifier was set up to provide the subject with feedback, and the second session—40 trials in which the subject had to control a horizontal bar on a computer screen—was conducted. Subjects were instructed to imagine a right-hand movement or a foot movement after a cue stimulus depending on the direction of an arrow. Bipolar electrodes were mounted over the right-hand representation area and over the foot representation area. Classification results achieved with (1) an adaptive autoregressive model (39 subjects), and @2) band power estimation (60 subjects) are presented. Roughly 93 percent of the subjects were able to achieve classification accuracy above 60 percent after two sessions of training.

Hestenes, J.; Pineda, J.A.; Silverman, D.S.; & Vankov, A. (2003). **Learning to control brain rhythms: Making a brain-computer interface possible.** *IEEE Transactions on Neural Systems and Rehabilitation Engineering, 11*(2), 181-4.
PMID #: 12899268
ABSTRACT: The ability to control electroencephalographic rhythms and to map those changes to the actuation of mechanical devices provides the basis for an assistive BCI. In this study, we investigate the ability of subjects to manipulate the sensorimotor mu rhythm (8-12-Hz oscillations recorded over the motor cortex) in the context of a rich visual representation of the feedback signal. Four subjects were trained for approximately 10 h over the course of five weeks to produce similar or differential mu activity over the two hemispheres in order to control left or right movement in a three-dimensional video game. Analysis of the data showed a steep learning curve for producing differential mu activity during the first six training sessions and leveling off during the final four sessions. In contrast, similar mu activity was easily obtained and maintained throughout all the training sessions. The results suggest that an intentional BCI based on a binary signal is possible. During a realistic, interactive, and motivationally engaging task, subjects learned to control levels of mu activity faster when it involves similar activity in both hemispheres. This suggests that while

individual control of each hemisphere is possible, it requires more learning time.

Kübler, A.; & Neumann, N. (2003). **Training locked-in patients: A challenge for the use of brain-computer interfaces.** *IEEE transactions on neural systems and rehabilitation engineering, 11*(2), 169-72.
PMID #: 12899265
ABSTRACT: Training severely paralyzed patients to use a BCI for communication poses a number of issues and problems. Over the past six years, we have trained 11 patients to self-regulate their slow cortical brain potentials and to use this skill to move a cursor on a computer screen. This paper describes our experiences with this patient group including the problems of accepting and rejecting patients, communicating and interacting with patients, how training may be affected by social, familial, and institutional circumstances, and the importance of motivation and available reinforcers.

McFarland, D.J.; Schalk, G.; Vaughan, T.M.; & Wolpaw, J.R. (2003). **The Wadsworth Center brain-computer interface (BCI) research and development program.** *IEEE Transactions on Neural Systems and Rehabilitation Engineering, 11*(2), 204-7.
PMID #: 12899275
ABSTRACT: BCI research at the Wadsworth Center has focused primarily on using electroencephalogram (EEG) rhythms recorded from the scalp over sensorimotor cortex to control cursor movement in one or two dimensions. Recent and current studies seek to improve the speed and accuracy of this control by improving the selection of signal features and their translation into device commands, by incorporating additional signal features, and by optimizing the adaptive interaction between the user and system. In addition, to facilitate the evaluation, comparison, and combination of alternative BCI methods, we have developed a general-purpose BCI system called BCI-2000 and have made it available to other research groups. Finally, in collaboration with several other groups, we are developing simple BCI applications and are testing their practicality and long-term value for people with severe motor disabilities.

Moore, M.M. (2003). **Real-world applications for brain-computer interface technology.** *IEEE Transactions on Neural Systems and Rehabilitation Engineering, 11*(2), 162-5.
PMID #: 12899263
ABSTRACT: The mission of the Georgia State University BrainLab is to create and adapt methods of human-computer interaction that will allow BCI technologies to effectively control real-world applications. Most of the existing BCI applications were designed largely for training and demonstration purposes. Our goal is to research ways of transitioning BCI control skills learned in training to real-world scenarios. Our research explores some of the problems and challenges of combining BCI outputs with human-computer interface paradigms in order to achieve optimal interaction. We utilize a variety of application domains to compare and validate BCI interactions, including communication, environmental control, neural prosthetics, and creative expression. The goal of this research is to improve quality of life for those with severe disabilities.

Search Terms for Brain-Computer Interface Technology

- Acoustic Stimulation
- Algorithms
- Amyotrophic Lateral Sclerosis (ALS)
- Analysis of Variance
- Artificial Intelligence
- Assistive Devices
- Auditory
- Augmentative and Alternative Communication
- Behavior Development
- Biofeedback/Methods/Physiology
- Biomedical Engineering
- Bionics/Instrumentation/Methods
- Brain/Anatomy/Diseases/Injuries/Mapping
- Calibration
- Cerebral Cortex/Palsy
- Chronic Disease
- Cognitive/Development/Processes/Psychology
- Communication (Thought Transfer)/Aids
- Computer/Assisted/Methods/Peripherals/ Science/Systems/User Training
- Conditioning
- Cortical Synchronization
- Cybernetics
- Diagnosis
- Disabilities
- Educational Technology
- Electrodes
- Electroencephalography
- Electronic Control
- Equipment Design
- Evoked Potentials
- Eye Movements
- False Negative/Positive Reactions
- Federal Legislation
- Feedback
- Image Processing
- Individual Development
- Information Science/Technology
- Instructional Innovation
- Intellectual Disciplines
- Magnetic Resonance Imaging (MRI)
- Magnetics
- Magnetoencephalography
- Man Machine Systems
- Mobility Aids
- Motor Activity/Neurons
- Movement/ Head Movements/Physiology
- Multimedia Instruction
- Neuro-degenerative/Neuro-muscular Diseases
- Neurological Organization
- Neuronal Plasticity
- Neurosciences/Neurosurgery
- Online Systems
- Paralysis/Therapy/Rehabilitation
- Pattern Recognition
- Photic Stimulation
- Prostheses and Implants
- Quality of Life
- Regression Analysis
- Rehabilitation/Programs
- Research and Development
- Robotics
- Self-Help Devices
- Sensitivity and Specificity
- Signal Processing
- Somatosensory Cortex
- Spinal Cord Injuries
- Stroke/Rehabilitation
- Task Performance and Analysis
- Technological Advancement
- Technology Transfer
- Therapy
- Thinking
- Touch
- User Computer Interface
- Vibration
- Video Games
- Vision/physiology
- Visual Cortex/Perception/Physiology

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