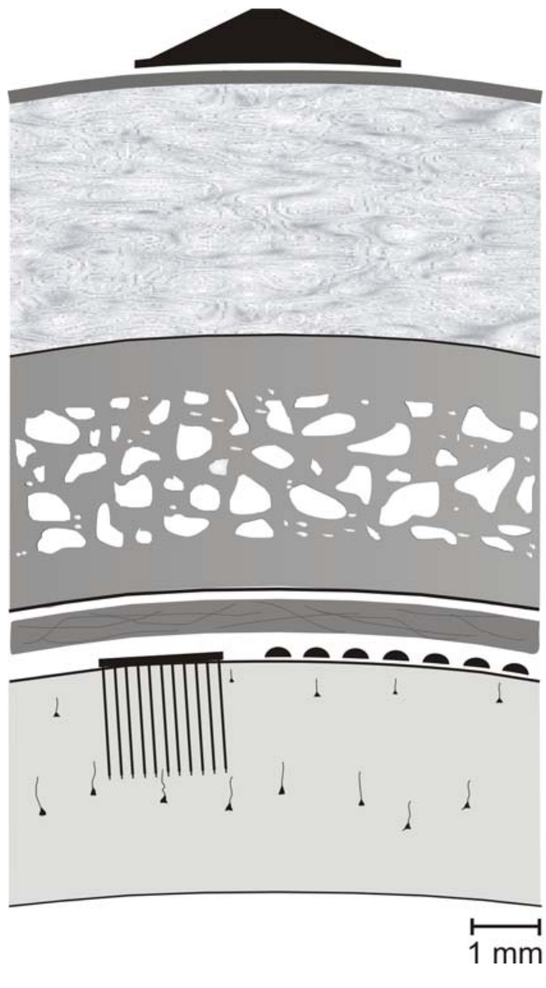
# BRAIN-COMPUTER INTERFACE TECHNOLOGY

Third International Meeting

*Making a Difference*

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Abstracts

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# Abstracts of Presentations

(In order of presentation)

# 15 YEARS OF BCI RESEARCH AT GRAZ UNIVERSITY OF TECHNOLOGY: ACTUAL PROJECTS

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Over the last 15 years, several prototypes of the Graz-BCI have been developed. Recent projects focus on the development of an asynchronous BCI, novel forms of feedback presentation and applications for communication and control.

**Towards a 3 (4) class asynchronous BCI:**

One of the most important challenges in BCI research is to switch from the cue-based to the asynchronous operation mode. For this purpose two important issues have to be addressed: The first deals with the detection or removal of signals, which do not origin from the brain (artifacts). The second concentrates on the discrimination between rest (idling) and motor imagery related brain patterns.

**Contribution of phase information:**

Almost all BCIs ignore the relationship between the different recording channels. Single-trial classification (offline and online) were conducted, which demonstrate that there is additional information in the phase-locking value (PLV), which represents the level of synchronization between signals from two specific electrode locations.

**Adaptive classifier**:

The aim of the adaptive on-line classifier is to automatically adapt to the changes in the EEG patterns of the subject and to deal with their long-term variations (non-stationarities). Two different types of adaptive classifiers were tested in on-line experiments, ADIM and ALDA. ADIM estimates the Information Matrix (ADaptive Information Matrix) to compute an adaptive version of the quadratic discriminant analysis. ALDA is an Adaptive Linear Discriminant Analysis (ALDA) based on Kalman Filtering. Both classifiers were analyzed with different types of features (AAR parameters, logarithmic BP)

**Control of FES in SCI patients:**

The perspective that BCIs may help humans with paralyzed limbs to restore their grasp function is not unreachable anymore. At this time we have experience with an asynchronous BCI in 2 patients with high spinal cord injury (SCI). Both have been equipped with a neuroprosthesis, either with surface electrodes or with an implanted system. One patient learned to induce 17-Hz oscillations by foot motor imagery which could be used for the realization of an asynchronous brain switch. The other one learned to reliable produce a power decrease of EEG-amplitudes during left hand movement imagination. Both patients were able to use the restored grasp function to grasp simple objects or a drinking glass.

**Control of a virtual keyboard in ALS patient**:

We report the case of a patient (60 years, male) who suffered from amyotrophic lateral sclerosis (ALS), being artificially ventilated. At the time the training started, the patient was totally paralyzed and had almost lost his ability to communicate. The training was performed at the patient's home and supervised via telemonitoring from the BCI-Lab in Graz. After a 3-months BCI training, he could use the 2-class cue-based spelling application Virtual Keyboard. After copy spelling, free spelling experiments have been carried out and the patient succeeded in writing a short message.

**Control of virtual environments:**

In recent experiments virtual reality (VR) is used as feedback medium. Performances of three different feedback (FB) conditions are compared: (i) abstract FB on a monitor (ii) VR-FB presented by a head mounted display and (iii) a highly immersive 4-wall projection environment ('Cave'). The usage of VR as FB was stimulating for the subject's performances.

**Software development:**

The BIOSIG project (http://biosig.sourceforge.net/, GNU general public license) is an open source software library for biomedical signal processing and contains various categories of signal processing, like feature extraction, classification, visualization and also the module "rtsBCI"; for real-time BCI experiments.

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## BION WIRELESS INTERFACES FOR PROPRIOCEPTION AND MUSCLE ACTIVATION

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We have developed a novel technology that allows multiple, separately addressable, wireless microstimulators to be injected into various muscle and neural targets to treat a wide range clinicaldisorders. Small clinical trials have been underway since 1999 demonstrating ability to prevent disuse atrophy, rebuild muscle function, reverse contractures and facilitate relearning of some voluntary control. We are now adding several sensing modalities to these implants to provide proprioceptive feedback of limb posture and movement for closed loop control of functional electrical stimulation (FES) to reanimate paralyzed limbs. These bidirectional interfaces with the peripheral nervous system could complement bidirectional interfaces with the CNS by turning command signals into functional limb movement and restoring kinesthesia.

# LABORATORY OF FUNCTIONAL NEUROELECTRICAL IMAGING AND BRAIN-COMPUTER INTERFACING AT FONDAZIONE SANTA LUCIA

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The laboratory of functional neuroelectrical imaging and brain-computer interfacing at Fondazione Santa Lucia is based on the joint work researchers with a bioengineering and clinical neurophysiology background.
The activity is mainly devoted to two aims: the non-invasive investigation of the motor cortical function under physiological and pathological conditions, through the development of advanced processing methods of the electroencephalographic signals; the development of a real-time EEG-based Brain Computer Interface (BCI) and the study of its use as an aid to enhance (or even to allow) the functional independence of persons with different degrees of motor disability.

Neuroelectrical Imaging consists in the estimation of distributed cortical activity, based on a priori knowledge of the conduction properties of the head and on specific scalp potential measurements (high resolution electroencephalography). This technique allows to overcome most of the spatial resolution problems of the EEG, and provide a direct match between functional activation and anatomic structures. This method can be used in conjunction with many methods developed for application to scalp data (ERD/ERS, coherence, Directed Transfer Function, etc). Current application include the study of the motor system of subjects with spinal cord injuries and preprocessing of EEG for BCI control.

Brain computer interface research has been conducted since 1998, through two projects funded by the European Commission (one still running) and several national ones. Bioengineering studies have been performed to optimize the EEG feature extraction and classification. Currently, the institute is leader of a joint national project for the development of an integrated assistive device, suitable to be controlled by a BCI input interface. Lately, the Fondazione Santa Lucia has promoted the aggregation of the "Italian BCI Interest Group", whose participants and activity are available at the URL http://www.braincomputerinterface.it

Italian Ministry of Health, Ricerca Sanitaria Corrente, Linea di ricerca E-IRCCS Fondazione Santa Lucia

# CORTICAL NEURAL PROSTHESES - CONTROLLING THE BIOLOGICAL INTERFACE

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Advances in electrical and biomedical engineering along with increased understanding of fundamental brain biochemistry and cell function provide powerful new tools to develop brain interfaces for diagnosis and treatment of brain injury and disease. Inserted neural prostheses hold tremendous potential for interfacing directly to brain and spinal cord neurons. These microfabricated devices take advantage of developments made in the electronics industry for design, fabrication, and materials. One of the impediments for clinical application of these devices is the degradation of recording performance over time. Close packing of cells and accumulation of extracellular material appears to be responsible for isolating devices from the neurons they are designed to monitor and/or stimulate. The development of this insulating sheath occurs via a series of reactive responses that are the consequence of the insertion process but are also sustained by the presence of these devices. Our goals have been to better understand these reactive responses so that new generations of devices and improved methods can be developed to eliminate or control the reactive responses and insure long-term device function. We are using immunohistochemistry and histochemistry with scanning laser confocal microscopy to produce three-dimensional data sets describing changes in cell distributions, morphology, and biochemistry. We continue to develop new methods for automated quantitative analyses of these data sets to provide precise measurements of device-related changes following insertion. We are studying the efficacy of local drug delivery via hydrogels or microfluidics to control the reactive responses and neuron survival and function. Our advances in these areas will be presented by focusing on several specific issues including the effects of insertion rates and tip designs on insertion-related damage, use of the neurovascular unit to index device-related changes in tissue organization and cell function and development of microfluidics for regional brain drug delivery. In order to describe insertion-related responses we are using an ex vivo thick brain slice preparation to provie real-time video imaging of tissue distortion and compression, vascular casting to describe vascular damage and responses, and 3-D imaging and image analysis to describe changes in neuron morphology, distribution, and biochemistry. These same methods are being used to describe cellular responses after devices have been in place for 6 weeks or longer. We have used this information to modify device designs and are presently testing new devices that provide tissue continuity around electrodes. Results from these experiments are being used to develop guidelines to improve the design and performance of microfabricated neural prostheses so that a consistent high level of performance for the life-time of the recipient is achieved.

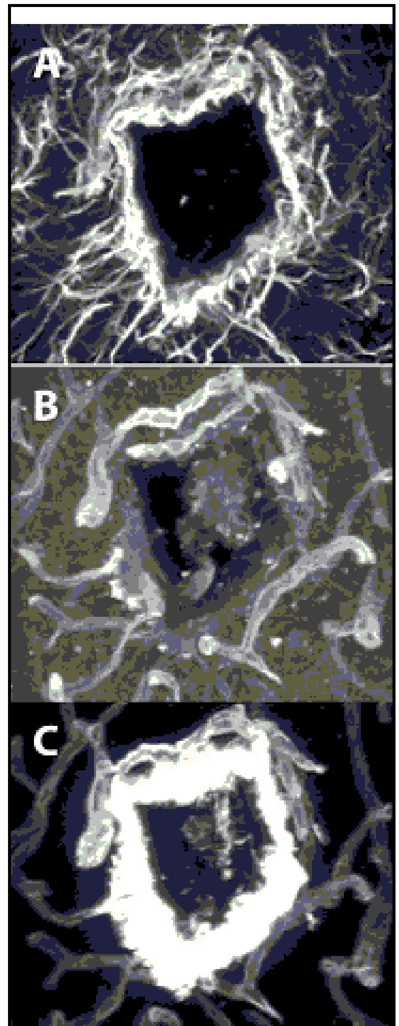


**Fig. 1** Sustained reactive responses observed 5 wks post insertion. (A) Glial fibrillary acidic protein (GFAP)-labeled astrocytes. (B) Glucose transporter-1-labled vascular elements. (C) Laminin-labeled extracellular matrix. Field width = 200 m.

Supported in part by NIH EB-000359, EB-002030, NS-044287.

**BRAIN-COMPUTER INTERFACES FOR 1-D AND 2-D CURSOR CONTROL: DESIGNS USING VOLITIONAL CONTROL OF THE EEG SPECTRUM OR STEADY-STATE VISUAL EVOKED POTENTIALS**

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We have developed and tested two EEG-based brain-computer interfaces (BCI) for users to control a cursor on a computer display. Our system uses an adaptive algorithm, based on kernel partial least squares classification (KPLS), to associate patterns in multichannel EEG frequency spectra with cursor controls. Our first BCI, Target Practice, is a system for one-dimensional device control, in which participants use biofeedback to learn voluntary control of their EEG spectra. Target Practice uses a KPLS classifier to map power spectra of 30-electrode EEG signals to rightward or leftward position of a moving cursor on a computer display. Three subjects learned to control motion of a cursor on a video display in multiple blocks of 60 trials over periods of up to six weeks. The best subject's average skill in correct selection of the cursor direction grew from 58% to 88% after 13 training sessions. Target Practice also implements online control of two artifact sources: a) removal of ocular artifact by linear subtraction of wavelet-smoothed vertical and horizontal EOG signals, b) control of muscle artifact by inhibition of BCI training during periods of relatively high power in the 40-64 Hz band.

The second BCI, Think Pointer, is a system for two-dimensional cursor control. Steady-state visual evoked potentials (SSVEP) are triggered by four flickering checkerboard stimuli located in narrow strips at each edge of the display. The user attends to one of the four beacons to initiate motion in the desired direction. The SSVEP signals are recorded from eight electrodes located over the occipital region. A KPLS classifier is individually calibrated to map multichannel frequency bands of the SSVEP signals to right-left or up-down motion of a cursor on a computer display. The display stops moving when the user attends to a central fixation point. As for Target Practice, Think Pointer also implements wavelet-based online removal of ocular artifact; however, in Think Pointer muscle artifact is controlled via adaptive normalization of the SSVEP. Training of the classifier requires about three minutes. We have tested our system in real-time operation in three human subjects. Across subjects and sessions, control accuracy ranged from 80% to 100% correct with lags of 1-5 seconds for movement initiation and turning. We have also developed a realistic demonstration of our system for control of a moving map display (http://ti.arc.nasa.gov/story.php?id=265&sec=4).

Supported by the Human-Centered Computing Project of the NASA Intelligent Systems Program, and the Information Technology Strategic Research Project of the NASA Computing, Information and Communications Technology Program.

# RESEARCH IN BRAIN-COMPUTER INTERACTION

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The Computer Vision and Multimedia Laboratory (CVML) research effort is oriented along three main directions: multimedia data indexing, retrieval and exploration; stochastic image processing, information theory, watermarking and data protection; brain-computer and multimodal interaction.

The long term goal of the Multimodal Interaction group is to augment "classical" interaction by means of non-invasive physiological recordings. Due to the CVML background, emphasis is put on theoretical modeling of the processes involved in the design of EEG-based interaction systems. Specifically, our work in the BCI context concerns brain source activity reconstruction to facilitate voluntary control using EEGs, information-theoretic studies of BCI performance measures, and assessment of user emotional status. On the practical side, theoretical results are validated by means of a Biosemi Active 2 EEG acquisition system with 64 electrodes. This system is currently being extended with other physiological sensors: ECG (electrocardiographic), EMG (electromyographic), GSR (galvanic skin resistance).

**Brain source activity reconstruction**

In the framework of a BCI project, there is need to properly distinguish between different mental activities. One way of doing it is through identification of the main active areas of the brain which are activated according to the current mental activities. We have developed reconstruction algorithms both for surface cortical sources and for in-depth volumetric sources. Cortical reconstruction algorithms are based on a diffusion procedure to smooth and enhance the EEG Laplacian, which is known to be a good approximation of the cortical activity. The EEG inversion procedure proposed for in-depth source reconstruction uses a statistical framework and a novel soft/hard focalization algorithm in order to retrieve relevant sources within the brain volume.We also studied the localization properties inherent to an EEG sensor system and used our results to derive principles for optimal sensor placement. We have proved that in this context optimally placed subsystems of electrodes can perform as well as normal systems with a much higher number of electrodes.

**Study on performance measures for Brain-Computer Interfaces**

Our goal is to analyze and assess the performance of a BCI, in particular using as a measure the information-transfer rate (ITR). By modeling the BCI as a noisy transmission channel, we have proposed a theoretical approach to determine which BCI parameters need to be tuned in order to maximize the ITR. Theoretical performance models have also been derived.

Several ITR definitions have been compared and their usage limitations have been found. We have also shown that an increase of the number of mental tasks only has limited effectiveness on the ITR. Finally, we have determined the optimal protocol speed for average-trial protocols, in order to allow proper selection of the number of trials that must be averaged.

**Detection of emotional states**

The objective of this study is to determine the emotional state of a HCI user using EEGs; this can be applied to the BCI domain as well as in various other HCI applications. For instance, considering a BCI user, the detection of a negative emotional state can be used as an error criterion in a reinforcement learning strategy.

There are two main brain pathways that are involved in the processing of emotions. First, the limbic system is essentially acting via the amygdala. Secondly, there are the frontal lobes where one can observe a lateralisation of emotions: the activation of the left (resp. right) frontal hemisphere is linked to positive (resp. negative) emotions. Our current work tries two differentiate negative and positive emotions using frontal lobes activity. For this, we stimulate subjects with images from the IAPS (International Affective Picture System) while recording their brain activity with EEGs. We then extract several features, such as power in the alpha band for each electrode, and use these features for classification.

Work supported in part by the Swiss National Ctr of Competence in Research (IM)2, Interactive Multimodal Information Management (http://www.im2.ch/), as well as by the European Network of Excellence SIMILAR (http://www.similar.cc).

## PREDICTION OF HUMAN VOLUNTARY MOVEMENT INTENTION IN REAL-TIME --- BCI PROJECT IN HUMAN MOTOR CONTROL SECTION, NINDS/NIH

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The movements of everyday human behavior are mostly executed in automatic, seamless sequences that require and capture minimum awareness of the components in the process. In experimental conditions however, people report perception of an urge to move that precedes voluntary movement. This subjective impression has been measured objectively using Libet's clock and is on average about 300 ms prior to EMG onset. EEG recordings of voltage changes show a rising negativity called the Bereitschaftspotential, beginning about 1.5 s prior to EMG onset, significantly earlier than the subjectively reported urge to move. This indicates that the brain mechanisms for generating a voluntary movement begin prior to the subjective intention, that is, unconsciously. It is the objective of our laboratory to detect the EEG signals that precede a voluntary movement event in real time, prior to the subjective experience of the intention to move.

In our high-resolution EEG study, subjects were asked to perform voluntary finger tapping using either hand. The timing of movement and which hand to move were freely chosen. Bilateral ERD in the beta band was observed over sensorimotor cortex before both left and right hand movements. From 2 s to 1 s before movement onset, ERD was only observed on left hemisphere before right hand movement, while ERD was present over both hemispheres before left hand movements. These results indicate that we might be able to predict movement onset and, as well, the laterality of human voluntary movement intention as early as 1 s before movement. However, our study also showed that the amplitude of early ERD is small, causing likely analytical difficulty for single-trial prediction.

We started a project "Brain-Computer Interface to Virtual Reality" (BCI2VR) to develop an intelligent system to enable processing and decoding EEG activity in real-time. The system integrates hardware interfacing, software programming and high-speed computing technologies. Testing results on a two-CPU PC workstation show that the delay due to mathematical computation is in a reasonable range of several ms. The kernel of the BCI2VR system is a computational algorithm for signal processing and pattern recognition. The computational procedure consists of four steps: data preprocessing; time/frequency feature extraction; spatial feature extraction; and feature classification. We have incorporated multiple methods in order to optimize prediction/decoding accuracy. Data preprocessing includes: signal reference methods (Laplacian, common reference); infinite impulse response/finite impulse response (IIR/FIR) frequency filters for noise reduction. Time/frequency feature extraction includes: filter methods; FFT-based classic spectrum estimation methods; auto-regressive model-based spectrum estimation methods; time-frequency representation; continuous/discrete wavelet transform. Spatial feature extraction includes: principal component analysis/independent component analysis (PCA/ICA) rotation/deduction; common spatial patterns (CSP) representation; discrete cosine transform/discrete wavelet transform (DCT/DWT); hidden Markov process model. Feature classification includes: linear distance classifier; Bayesian probability classifier; artificial neural network (ANN) classifier; supporting vector machine (SVM). Further, BCI2VR reserves a plug-in function to incorporate add-on computational methods. BCI2VR also provides an output interface for controlling external devices. We have completed the frame work for BCI2VR and are still working on the details of system components.

We have conducted real-time prediction of human movement intention using the current BCI2VR system with a few normal subjects. The experimental procedure for real-time prediction consists of two sessions: (1) data calibration for construction of prediction model; (2) real-time prediction of movement intention with/without feedback of prediction information. The subjects were asked to make a decision (at their own pace) of which hand to move after a "start" cue was given. They then executed the movement as soon as they made their decision. EMG signals were recorded to monitor movement. According to empirical knowledge of EEG features during voluntary movement, we reduced the number of electrodes from 122 to 29. The 29 electrodes were placed on sensorimotor area, supplementary motor area and pre-motor area bilaterally. We employed the following computational strategy: Laplacian reference, FFT estimation of power spectrum with logarithm representation, CSP spatial filter, and Bayesian probability classification. We employed the Fisher Criterion to measure mean distances among classes. The Fisher Criterion is considered a good indicator of classification accuracy as it judges both mean distance and sample variance among different classes. The Fisher assessment spans all possible time and frequency windows, and the best timing and frequency components were automatically judged for making a prediction of the movement intention.

We have studied several subjects extensively so far. Classification was made based on an EEG spatiotemporal feature vector, and probability was calculated using a pre-determined model. With a prediction time criteria of 0.8 s before movement onset, the real-time prediction of human voluntary movement was achieved with an accuracy as high as 80%.

**IMPLANTABLE INTRACORTICAL NEUROPROSTHESES: DEVICES AND EXPERIMENTAL STUDIES**

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Our Neural Engineering Laboratory is working on both new implantable microdevices for interfacing with the brain and adaptive algorithms for decoding cortical signals. We have developed a silicon-based microprobe technology that has proven to be effective for recording neural activity from neuronal populations for sustained time periods. This probe technology is currently being extended to include polymer substrates, chemical interfaces for drug delivery, advanced coatings for improved biocompatibility, and integrated electronics for wireless communication to the outside world. We have also investigated (in behaving rats) cortical control without the need for a priori training (naïve cortical control) and alternative locations within the cortex for cortical control signals. Currently, we are investigating correlations between different electrophysiological signal types, specifically, local field potentials (LFPs), spikes, and electrocorticograms (ECoGs), during brain-computer interface tasks. Our linear single shank electrode allows us to sample the layers of the neocortex during a cortical control task. Preliminary data shows that deeper layers of the cortical LFPs become more active in the 0-20 Hz range when rats are required to modulate their spiking activity.

## STROKE MOTOR LEARNING AND MOTOR CONTROL

Janis J Daly, Guang Yue, Robert L Ruff, Yin Fang, Mark Dohring, Elizabeth Perepezko, Jean Rogers, Kristen Roenigk, Jennifer Gansen, Jessica McCabe, Michael Fu.
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Conventional therapies fail to restore normal gait and upper limb function to many stroke survivors. The mission of the Stroke Motor Control/Motor Learning Laboratory is to develop innovative and more effective motor learning interventions.

We developed an eight-channel functional neuromuscular stimulation (FNS) system utilizing intramuscular (IM) electrodes for gait retraining. In randomized, intervention studies, for stroke survivors (>12mo), we found that FNS-IM produced statistically significant, greater knee flexion coordination, swing phase knee and ankle flexion, and stance phase components, versus No-FNS treatment (that included coordination exercises, weight supported treadmill training, and over ground gait training).

We developed upper limb interventions that integrated motor learning (ML) methods with technology applications of FNS (FNS-ML) or shoulder/elbow robotics (ROB ML). In a randomized intervention study of subjects with chronic deficits, we found that significant gains were produced by FNS ML and ROB ML in impairment and functional measures. Though these results were promising, not all subjects were restored to normal. The cortical processes that drive motor control are not well understood in stroke survivors. In a series of pilot studies we investigated aspects of cortical function in stroke survivors. We enrolled ten subjects with persistent (>12mo) arm coordination deficits and eight healthy controls. Simultaneous data was obtained for electroencephalography (EEG; electromyography (EMG, triceps); and movement onset (custom device). EEG and EMG were trigger-synchronized. Regions of cortical interest were ipsi-lesional sensorimotor and frontal areas.

Study 1 showed that stroke survivors had both prolonged cognitive planning time and elevated cognitive effort. The motor task was a 14cm, linear movement in the horizontal plane, accomplished using shoulder flexion and elbow extension. Onset of motor planning was defined as the onset time of EEG-derived, movement-related cortical potential (MRCP). Duration of cognitive planning was defined as the time period from MRCP onset to EMG onset. Level of cognitive effort was defined as the amplitude of MRCP. In comparison to controls, stroke survivors exhibited abnormally prolonged cognitive planning time and abnormally elevated amplitude of MRCP in sensorimotor and frontal regions.

Study 2 showed that there was a moderately high and significant correlation between smoothness of movement and cognitive motor planning time. The motor task required smooth tracing of a circle template beneath the hand by using the shoulder and elbow muscles. Stroke subjects exhibited abnormally prolonged cognitive planning time in the sensorimotor and frontal regions. There was a moderately high and significant correlation between uncontrolled jerkiness of movement and prolonged cognitive planning time in sensorimotor ($r=.64$; $p=.01$) and frontal ($r=.64$; $p=.009$) areas. Study 3 showed that for stroke survivors ($n=7$), there was a correlation between cognitive delay and muscle activation latency ($r=.71$; $p=.075$), during performance of the linear motor task.

The purpose of study 4 was to investigate time-dependent coherence between sensorimotor cortical area (EEG) and anterior deltoid EMG signal during a linear motor task performed by shoulder/elbow (eight controls and ten stroke survivors). EEG and EMG signal were analyzed from movement onset to 3sec after movement onset. Dynamic coherence was calculated using multivariate autoregressive modeling. Preliminary results showed that control subjects exhibited strong coherence in band between anterior deltoid muscle and the sensorimotor cortical region. Controls also exhibited strong coherence in lower band immediately after movement onset. Stroke survivors did not show significant coherence between anterior deltoid EMG and cortical sensorimotor EEG signal.

Study 5 showed that three subjects treated with robotics and motor learning improved in both cognitive planning time and cognitive effort level ($p=.05$; and $p=.05$), respectively.

We appreciate the opportunity to learn from the esteemed participants at the BCI Conference 2005.
Acknowledgements: DVA, Rehabilitation Research and Development Service, B2226R, CoPIs Daly & Ruff; B2801R, PI Daly; NIH (HD36725) PI Yue.

**BRAIN - COMPUTER INTERFACE (BCI) RESEARCH AT THE UNIVERSITY OF SOUTH FLORIDA COGNITIVE PSYCHOPHYSIOLOGY LAB: THE P300 EVENT-RELATED POTENTIAL**

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The P300-BCI Speller, first described by Farwell and Donchin (1988) adapted the so-called Oddball Paradigm (OP) as the operating principle of the BCI. In an OP, the subject is presented with a Bernoulli sequence of events, each belonging to one of two categories. If the subject attends to the sequence, and one of the categories occurs less frequently than the other, events from the rare category elicit the P300 component of the ERP. In the P300 Speller, the user observes a 6x6 matrix containing alphanumeric characters and symbols, which serve as a virtual typing keyboard. The columns and rows of the matrix intensify at random, in a serial sequence, and the user's task is to count the number of times a particular character flashes (i.e., attend to a particular item). This creates an OP with the row and column containing the "typed" character serving as the rare category. The row and column containing the attended character elicit a P300, while the other 10 rows and columns do not. This paradigm has been the benchmark in P300-based BCI systems, and in the past few years the P300 matrix paradigm has been solidified as a promising communication tool as the results of several data competitions and published studies have reported near perfect character classification. However, most of the research has been conducted with able-bodied subjects and within a limited time frame. Our work with locked-in and severely disabled amyotrophic lateral sclerosis patients has indicated that the 6x6 matrix system may not be the most practical system to use with locked-in patients.

While all patients showed differential responses to the attended and non-attended items, in a standard oddball sequence, not all patients were successful using the 6x6 matrix. Some nearly locked-in patients expressed difficulty attending to the rapid presentation rate of the 6x6 matrix, while others produce involuntary eye movements that prevent them from seeing every presentation. Furthermore, new and challenging logistic problems arise when working with patients, and in their homes. The electrically noisy environment is a source of artifacts in the data, (e.g., respirators, phones, pets, etc.). The needs of the patients are also important, many patients would be better suited with a system that has a limited number of choices, particularly if the 6x6 matrix is difficult to use. These findings led us to begin testing a system that, while still utilizing the OP principles, reduces the total number of stimuli employed. In the current version the subject is presented with a sequence of four events: Yes, No, Pass, and End. We also presented stimuli in one of three presentation modalities, auditory, visual, or concurrent auditory/visual presentation. All visual stimuli were presented at fixation and subtended approximately 14 degrees of visual angle, to minimize visual deficits. The auditory mode was included because it is quite possible that patients may have difficulty opening and moving their eyes. We have also conducted many sessions (10 or more) with the users to examine the effects of long term use. Our work suggests that P300 response classification is stable across multiple sessions for individual users. In addition, the 4 choice data suggest that different modalities are better suited for different users. A flexible BCI system that can provide a user with more than one possible paradigm and stimulus set is essential in meeting the needs of each BCI candidate.

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# 3D CORTICAL CONTROL OF AN ANTHROPOMORPHIC ARM UNDER DIRECT VISUALIZATION

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The BCI research in our lab is firmly grounded in basic neurophysiology of motor control. We have previously shown that natural arm trajectories can be reconstructed from motor cortical activity and that the same signals can be used to predict intended realtime movement velocity in the absence of actual arm movement. We have demonstrated a monkey controlling a cursor in 3D virtual reality using cortical output. Recently we have trained a monkey to control an anthropomorphic robotic arm under direct visual feedback. The monkey uses the arm under brain control to reach for fruit presented at various targets in 3D space and retrieve the food back to its mouth for consumption. The control algorithm requires no prior knowledge of the mapping between neuronal firing rates and natural hand movement, making it suitable for disabled human use. In the future we plan to study the cortical representation of wrist and hand movements, and later apply the neurophysiological findings to prosthetic control.

Support contributed by NIH-NINDS-NO1-NS-2-2346

# UCLA NEUROENGINEERING PROGRAM AND BCI RESEARCH

Jack W. Judy
UCLA

Over the past several years we have used NSF Integrative Graduate Education and Research Training (IGERT) Program funding to expand the existing synergies between the UCLA Brain Research Institute (BRI) and the School of Engineering and Applied Science (SEAS). Specifically, the NET program has promoted the application of new engineering technologies to neuroscience, including micromachining and microelectromechanical systems (MEMS) and wireless-sensor-network technologies. For example, we are designing a comprehensive wireless neural recording, archiving, hosting, and stimulation system that uses miniature-scale wireless-enabled embedded computers (about the size of a quarter) as the local neural recording and stimulation nodes. These computers (otherwise known as motes) are capable of multi-channel data acquisition, signal processing, data reception, and transmission via an 802.15.4-compliant radio. This approach is in contrast with methods for developing such compact, low-power, bi-directional wireless neural interfaces: developing custom integrated circuits (costly and long development time) to assembling PC-based commercial off-the-shelf components (large and power intensive). In regards to our BMI efforts, we are investigating the design of BMIs in an awake, freely behaving rat model. These rats are trained to use the BMIs by controlling neuronal firing on recording electrodes. Parameters under test to determine the reliability of control include trained patterns of neural activity, interpretation schemes by the computer, and appropriate electrode selection. Other cortically implanted electrodes are used to communicate data back to the rat as sensory or neural reward signals. Behavioral tasks are performed to determine how the rats use the brain machine interface to assist in accomplishing operant tasks.

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**BRAIN INTERFACE RESEARCH FOR ASYNCHRONOUS CONTROL APPLICATIONS**

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Neil Squire Society and University of British Columbia

The Brain Interface (BI) Laboratory at the Neil Squire Society has been conducting research into a direct brain computer interface for self-paced (or asynchronous) control applications for over thirteen years. Our main focus is the development of a brain-activated switch for asynchronous control of various tasks in natural environments. More explicitly, we design technologies that will work whenever a user intends control, but also remains neutral during the periods when there is no user intent to control (i.e. they are idle). Examples of self-paced control applications are turning on lights, changing television channels, and interacting with a computer.

During real-world control people expect that their interface technology will stay neutral when they are not controlling a device (e.g. they are talking, daydreaming, thinking about a problem). Thus, BI technology must support what we call idling. A transducer that idles well will produce a stable output when the person using the transducer is not controlling the transducer (i.e., the user is in a "No Control"; state). This is analogous to a car engine in that when no gas is applied (the No Control state), the engine idles at a stable rpm. Most other research groups have not reported how well their BI technologies idle.

Self-paced or asynchronous control applications (i.e. those that require idle support) need specific signal processing algorithms. The Neil Squire Brain Interface Lab specializes in advanced signal processing for discrete self-paced control applications that utilize motor-related potentials. Thus, not only do we strive to improve the accuracy of a system in determining a user's control intentions, we also focus on the periods when the user is not controlling the interface. Thus, an emphasis of our work is to minimize false activations that occur during idle periods. Our most recent offline results for the LF-ASD brain switch showed that both able-bodied individuals and those with spinal cord injuries could activate the switch with a mean hit rate of 72% at false activation rates of less than 2%, which translates to total system classification accuracies of over 97%. (Note that we have found that false activation rates greater than 2% lead to user frustration and unusable systems, thus we bias the ROC curves towards lower false activation rates.) Even though these error rates appear quite promising, they are not sufficient for self-paced real-world usability. Further improvements are underway by: 1) investigating alternative EEG signal features; 2) expanding system bandwidth by supporting multiple intentional control states; and 3) developing methods to effectively handle ocular artifacts. We are also expanding the capacity of our lab by applying self-paced signal processing and testing methods to other BI paradigms such as implanted electrode arrays for sensory neural prostheses in animal models.

Another major focus of our lab is the development of common language in the BI community. We continue to publish perspective papers on language issues, proposing functional models and taxonomies to address the lack a common language for describing and discussing BI technology and its evaluation. Our intent is to document and validate our best thinking in this area and publish a perspective that will stimulate discussion. We support others to do the same with the belief that focused discussion on language issues will accelerate the inherently-slow natural evolution of language selection and thus facilitate education, technology sharing, objective comparison and cross-group validation of published findings.

Since the last Brain Computer Interface workshop in 2002 our lab has grown. The team now consists of three senior researchers, a lab manager, three Ph.D. candidates and two Masters' students. Future direction is to add physiology, neurophysiology and surgical support to explore more invasive BI methods.

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**HAND ORIENTATION CONTROL IN MOTOR CORTEX**

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Our primary research interest is in the area of cortical control of voluntary arm movements. We seek not only to understand how the central nervous system controls movement, but also to explore how we can use this information to restore function to those suffering from neuromuscular disease and/or paralysis. Classically, reaching movements have been broken down into three phases: a transport (translation) phase, an orientation (rotation) phase and a grasping stage. In the past 25 years, there has been considerable research in non-human primates relating motor cortical activity with hand translation (i.e. hand position and velocity) but virtually no research into the cortical representation of hand orientation. Our lab investigates the relationship between hand rotational kinematics (i.e. orientation angle and angular velocity) and motor cortical activity (single-units, field potentials, and epidural electrocortiocography). We have developed a novel behavioral paradigm in a primate virtual reality simulator that can systematically vary both hand position and orientation (yaw, pitch and roll) throughout the workspace in a random fashion. Our single-unit data suggests that both hand rotation and translation are well represented in motor cortex during reaching tasks. From a neuroprosthetics point of view, being able to simultaneously decode desired 3D position and 3D orientation from a population of cortical neurons could allow paralyzed individuals to control robotic arms so that, for instance, they can accurately transport a cup of coffee to their mouths without spilling and then tip it to take a drink.

**BRAIN-MACHINE INTERFACES: COMPUTATIONAL APPROACHES AND HYBRID HARDWARE DEVELOPMENT FOR MULTI-CHANNEL NEURAL DATA ANALYSIS**

Justin C. Sanchez, Jose C. Principe, John G. Harris, Toshi Nishida, Rizwan Bashirullah
University of Florida

The University of Florida Brain Machine Interface (BMI) consortium is pursuing synergistic advances in many disciplines ranging from system and cognitive neurosciences, neurophysiology, neurosurgery and related clinical areas to biomedical, electrical, mechanical, materials science engineering and computer science. BMI research was initiated in the Computational NeuroEngeineering Laboratory (CNEL) which has included a 5 year high visibility research effort (DARPA funded) with Duke University, MIT, SUNY and a Company Plexon. At the core of BMI technology is the growing ability to use electrophysiological methods to extract information about intentional brain processes from the raw electrical activity of large populations of single neurons, and then translate these neural signals into models that control external devices. The second component of our research is to develop real-time digital signal processing devices to implement BMIs. In conjunction with the Interdisciplinary Microsystems Laboratory (IML) we are pursuing to design MEM microelectrode arrays in flexible substrates to be small enough to probe the appropriate cell assemblies and to minimize injury to brain tissue. The analog division of the CNEL lab is designing ultra lowpower VLSI bioamplifiers that draw currents in the tens of microamps. To contend with the demanding bandwidth requirements of BMIs are also developing hybrid (analog-digital) signal compression schemes to reduce the bandwidth required to represent spike trains and bring the data from beneath the skin to the outside for further processing. The Integrated Electronics Center (IEC) is designing ultra low-power wireless transmission with megabit/sec bandwidths to transfer the subcutaneusly data to an external receiver. The digital component of the CNEL lab is modeling the nonstationary spatial temporal structure of the spike train data to accurately find the mappings from multichannel spike trains to multiple outputs (MIMO adaptive systems) that will control the robotic devices. The Applied Digital Design Laboratory (ADD) is implementing the predictive signal processing models with thousand of free parameters in real time and in small, eventually portable, DSP boards. All of the technological advancements are synergistically integrated in the Children's Miracle Network Animal Neurophysiology Laboratory (CMNANL) within the UF Brain Institute. Here we are developing the experimental protocols, defining the basic constructs of motor electrophysiology, and testing in vivo the instrumentation in behaving animals.

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**BRAIN-COMPUTER INTERFACE RESEARCH IN TSINGHUA UNIVERSITY**

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The BCI research in the Institute of Neuroengineering of Tsinghua University is focused on non-invasive scalp electroencephalogram (EEG) based methodology, including dependent and independent method. The main interests include developing effective EEG signal processing algorithms and implement some practical BCI systems, which can help the motion disabled with basic device operation in surrounding environments.

Since 1999, we have successfully developed a BCI system based on steady state visual evoked potentials (SSVEPs). It has been proved an applicable system through extensive tests in laboratory demonstration and clinical applications. A BCI-based environmental controller has been tested on 11 volunteers with spin cord injury in the Rehabilitation Center of China. The features of the system can be summarized as:

(1) High information transfer rate.

With the aid of large number of possible decisions per selection and high frequency detection accuracy, the average transfer rate of 16 volunteers in laboratory is 42 bits/min.

(2) Less training is required.

Through offline data analysis and online operation with feedback, the user can achieve a good performance within half an hour.

(3) Adaptability across wide range of subjects.

We have developed an optimal channel selection method, which can greatly improve the system applicability. With subject specific lead selection, above 90% of the users can use the system successfully. The transfer rate of tests in lab is between 29 and 57 bits/min, ensuring stable communication capability.

(4) Easy system preparation.

A portable system with the use of digital signal processor has been developed. Only a pair of bipolar electrodes for data acquisition makes the recording preparation much convenient.

We have also been engaged in the research on BCIs using event-related P300 potentials, and movement-related potentials (MRP) respectively. An effective signal processing framework for detection of different mental states has been proposed. We made use of temporal-spatial pattern analysis to do signal preprocessing and feature extraction, which can enormously improve the signal-to-noise ratio of multi-channel task-related EEG. As the winners of two data sets (P300 and Self-paced typing) in BCI Competition 2003, we have developed an independent component analysis (ICA) based P300 enhancing method and a spatial subspace decomposition algorithm towards movement-related EEG during self-paced typing.

Our future plans are as follows:

(1) To further improve the system performance of VEP-based BCI and expand the applications such as environmental controller, robot manipulation, and other device control in special environments.

(2) Go deep into the EEG signal processing technology to improve the feature recognition in different mental states.

(3) We will also dedicate to investigate the combination of BCI and functional electrical stimulation (FES), which should be used in neurorehabilitation and neuroprosthesis.

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**NEURAL ENSEMBLE ACTIVITY FROM MULTIPLE BRAIN REGIONS PREDICTS KINEMATIC AND DYNAMIC VARIABLES IN A MULTIPLE FORCE FIELD REACHING TASK.**

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Just what the motor cortex is encoding when we reach and retrieve an object is still under debate. Perhaps insight may be gained by focusing on how it interacts with other cortical regions such as the somatosensory cortex and more rostral and caudal motor areas as well as lower brain regions like the VPL thalamus. In order to gain insight into how these multiple brain regions interact to formulate reaching movements under differing dynamic constraints we trained rats to grasp a manipulandum handle while making multi-joint reaching movements as the manipulandum imposed several different force fields. The two force field paradigms we chouse were a constant force paradigm and a spring paradigm. In both versions the manipulandum randomly switched in a block fashion between large force and small force versions of the fields, which the rats learned to compensate for while maintaining their null field kinematics (Francis et al. IEEE TBME Vol. 51, No. 6 2004). Seven rats were implanted with a 32 channel microwire array that spanned 5 mm covering both the caudal and rostral motor cortex as well as the sensory cortex while a second implant was placed in the rostral VPL, which has been shown to respond to proprioceptive and cutaneous stimuli (Francis et al SFN meeting 2003). We generally obtained 40-60 neurons per animal and recorded 16 LFP channels in the cortex and 8 LFP channels in the rVPL. We used multiple linear regression models to fit the neural data to either kinimatic or dynamic variables such as position, work, velocity and the force produced by manipulandum. In general the best predictions were to the force as well as position (average r = .7). In addition we found that neurons of the sensory-motor cortex of the rat segregate into the same groups of cells seen in the primate that is tonic, phasic-tonic etc? We also found a set of cells that predicted the time of the next self paced movement by increasing their activity steadily until it peaks predicting the moment that the reaching movement will occur.

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**WIRELESS BRAIN COMPUTER INTERFACE FOR DISABLED INDIVIDUALS**

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A compact, convenient, and easy-to-use wireless brain-computer interface (BCI) system is introduced to allow limited but extremely valuable communications using brain wave for completely paralyzed patients, who have also lost their ability to speak. The data acquisition system is based on Cleveland Medical Devices Inc.'s FDA approved BioRadio 150® system, which consists of a compact integrated 8 channel MicroSynth™ RF radio transmitter, a receiver, and a laptop PC. However, a smaller, quarter-dollar size two-channel version (the BioRadio® Jr.) is also available for developing the BCI system. The transmitter acquires, amplifies, digitizes, and transmits EEG (Electroencephalogram)/ERPs(event related potentials) signal to a nearby receiver up to about 50 feet through walls. The receiver attaches to the USB port of any personal computer (PC), stores and processes the acquired EEG/ERPs signal. A specific software package is developed for delivering user defined auditory/visual stimuli, extracting ERPs, and classifying ERPs corresponding to each stimulus continuously in real-time. The focus of this study is to classify match/mismatch ERPs based on a classification fusion strategy that was developed to classify multi-channel ERPs by fusing the classification results of all channels using a majority rule [1]. Results from this study yields very high match/mismatch classification accuracies rapidly which is crucial for the practical implementation of the BCI system (see Table 1). It was shown that the results of the fusion rule classifier were consistently superior to the results of the rule that selects a single best channel.

**Table 1** Classification accuracy of 4 subjects at different number of single-trial repetitions (r)

| **Trials** | **Subjects** | | | |
|---|---|---|---|---|
| r | A | B | C | D |
| 4 | 91.56 | 87.56 | 83.9 | 84.78 |
| 8 | 96.94 | 93.75 | 91.7 | 92.31 |
| 16 | 99.75 | 98.38 | 97.38 | 98 |

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**MACHINE-LEARNING APPROACHES TO BCI IN TUEBINGEN**

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We present an overview of the joint work of members of two groups based in Tuebingen, Southern Germany:
- the NeuroTeam (led by Dr. Martin Bogdan) at Tuebingen University's Computer Science department (Prof. Wolfgang Rosenstiel).
- the Department of Empirical Inference (led by Prof. Bernhard Schoelkopf) at the Max Planck Institute for Biological Cybernetics.

Our emphasis is on machine-learning approaches to BCI, i.e. using modern adaptive algorithms to identify automatically which features of brain signals are most informative. BCI publications frequently report good performance from such techniques after only a two- or three-hour training session with a healthy subject, but it is unusual to hear of patients achieving results so quickly. The most successful approaches to patient BCI are still those in which the user rather than the computer has to do most of the learning, and this usually takes many weeks. Our long-term goal is therefore to bring the benefits of a machine-learning approach to patients, and we cooperate closely with Professor Birbaumer's department in Tuebingen in order to do this.

We are working continuously to develop visualization techniques for the fast and flexible screening of data. In addition to applying these techniques to patient data, we also perform experiments on healthy subjects in order to develop new approaches to BCI. These include:

- Motor imagery experiments in EEG and MEG (healthy subjects) and in ECoG (implanted patients at the Epileptology clinic, Bonn). We have demonstrated good performance in all three settings, and many users have been able to use a decision-tree speller to write by modulating their mu activity.
- The development of new paradigms, for example a system in which a binary decision can be expressed by shifting covert attention to one of two auditory stimulus streams. Future development of such systems will be important for patients for whom mu systems do not work and whose vision is poor.
- Visual speller experiments, in which we explore the psychophysical parameters of the stimulus display that lead to the best performance.

A common ingredient to all of our work is the use of reliable modern classification and regression techniques such as Support Vector Machines. The SVM is particularly well-suited to BCI data because it is a so-called kernel method, whose computational complexity depends far more on the number of training trials than on the number of features used to describe each one. For brain signal data, in which large numbers of trials are difficult to collect, and in which each trial contains many thousands of sample points across dozens of channels, this is a great advantage. Another common factor is the importance of feature-selection methods that isolate the relatively small proportion of useful information that there is in the incoming data stream. In particular we have shown that the technique of Recursive Feature Elimination, especially in combination with Independent Components Analysis, localizes the useful information in the brain very reliably.

Our planned future directions include the extension of the above work to multi-class and continuous-output settings, the application of MEG to patients in order to provide a faster and more accurate screening of likely successful approaches, and the development of machine-learning techniques that are invariant with respect to session-to-session or even use-to-user differences.

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# UNIVERSITY OF MICHIGAN DIRECT BRAIN INTERFACE: 2005 UPDATE

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The University of Michigan Direct Brain Interface (UM-DBI) project is pursuing the development of a brain-computer interface for the operation of assistive technologies based on the detection of event-related activity in human electrocorticogram (ECoG). Types of activity utilized include both event-related potentials (ERPs) and event-related desynchronization and synchronization (ERD/ERS). Research subjects are patients in epilepsy surgery programs who have subdural electrodes implanted for clinical purposes unrelated to the research objectives. Movement-related activities (instead of preferred motor imagery activity) have until recently been used for documentation of movement onset in order to assess detection accuracy during off-line analysis. The target interface is an asynchronously operated momentary switch that could replace a mechanical switch for operation of assistive technologies.

The UM-DBI project is composed of three components: development of signal processing and detection methods through off-line analysis of recorded data, on-line functional evaluation and feedback experiments, and functional magnetic resonance imaging (fMRI) studies.

An ECoG database has been accumulated for the development and testing of algorithms off-line. This data base includes 352 datasets, from 44 subjects. Each dataset contains recordings from 15 to126 subdural electrodes made while subjects performed approximately 50 repetitions of a voluntary action. In total, there are over 15,000 ECoG recordings from subdural electrodes in the database. The current detection method is a quadratic detector based on a two co-variance signal model (QUAD) (see Chun, et al. 2005 in these proceedings). The QUAD method provides improved detection accuracy along with improved response time over our previous cross-correlation template matching (CCTM) method which has been previously described (Levine, et al., 2000).

On-line feedback experiments examine the ability of subjects to learn to operate the direct brain interface. To date, feedback experiments have been based on the CCTM method. Some subjects have been able to improve their operation of the system during the two hour feedback session with one subject improving DBI operation from 90% hits with 45% false positives to 90% hits with 10% false positives (Levine, et al., 2003). Another subject was able to transition from operation of the interface using actual tongue movements with 90% hits and 13.5% false positives to operation using imagined tongue movements with 82% hits and 16.3% false positives. Upcoming experiments will utilize the QUAD detection method to improve accuracy and interface response time in experiments utilizing imagined movements.

FMRI experiments are intended to evaluate the feasibility of using fMRI to plan the placement of electrodes for operation of a DBI. Two subjects who had previously participated in ECoG experiments performed both actual and imagined movements during fMRI scanning. Some agreement was found between the modalities, but many outliers exist. Confounding factors in the comparison included extended time (average 16.5 months) and surgical resection between ECoG and fMRI recording (Swaminathan, et al., 2004). Therefore, future subjects will participate in fMRI scanning prior to ECoG recording.

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**TIME-FREQUENCY-SPACE APPROACHES FOR EEG-BASED BRAIN-COMPUTER INTERFACE**

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Our laboratory has investigated new algorithms for classification of motor imagery (MI) tasks for brain-computer interface (BCI) applications by analyzing scalp EEG signals. Broadly speaking, these methods can be divided into two categories: time-frequency (TF) analysis and spatial source analysis. In our TF analysis, the spatiotemporal EEG data is decomposed into time-, frequency- and spatial-components. The characteristic features of left- or right-hand MIs can be extracted and/or synthesized from these multi-dimensional components. The EEGs are decomposed into a series of frequency bands; an energy profile is extracted by enveloping the oscillatory time series at each electrode within each frequency band; a spatial pattern of energy distribution presents on each TF pair; TF weights determined by training process are used to synthesize the contributions from all the TF pairs. By applying EEG inverse techniques, the source representations can be derived from the blurred scalp potentials. Before inverse calculation, preprocessing procedures - Laplacian spatial filtering, band-pass filtering, noise normalization, SVD denoising and independent component analysis (ICA), are used to extract MI-task-related signals from single trial recordings. Based on different source models, single- or two-dipole fitting procedures, or distributed current density estimation can be performed to evaluate which side of the brain (either left or right) presents dominant activity. All the above algorithms have been tested using either a publicly available dataset of MI EEG, or data collected in our lab in human subjects performing MI experiments. The results are promising, suggesting that these newly developed algorithms may provide useful alternatives for noninvasive BCI applications.

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# A BCI SYSTEM FOR CONTROL OF A PROSTHETIC HAND AND REMOTE DEVICES

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This paper describes research work carried out at the University of Malaya to develop a Brain Computer Interface (BCI) system to control a prosthetic hand and other remote devices.

The University of Malaya (UM-BCI) system consists of the following elements:

1. A BCI box containing:
   An EEG amplifier and filter
   ADC USB communication port/Bluetooth RS232 unit

2. A Bluetooth enabled computer containing:
   A main controlling program
   Signal processing programs

3. Electrodes placed on the scalp

4. Devices;
   A prosthetic hand with Fuzzy Logic Controller wired to the BCI box
   Four remote LED's with Bluetooth RS232 communication unit

Brain EEG signals are acquired through 2 or 4 electrodes placed on the scalp of a subject.

In the BCI box, the EEG signals are amplified and filtered. The filtered signals are fed into separate analog-to-digital converters to be digitized. The digitized data are communicated to a computer through either a universal serial bus (USB) wire or a wireless Bluetooth RS232 unit.

Signal processing, feature extraction and classification of the signals are carried out in the computer. The classification results are sent out either through the USB port or the wireless Bluetooth RS232 unit to the Fuzzy Logic control in the BCI box to control the prosthetic hand.

The UM-BCI system is designed so that the BCI box communicates with the computer through standard communication protocols commonly found in palmtops, laptops and desktop computers. The two communication options provided are either a USB communication port or a wireless Bluetooth RS232 unit. This is selected so that the BCI system can be designed to be independent of the processing unit - the computer. As and when more compact and more powerful portable computers become available, they can be used as the processing unit of the BCI as long as they possess a USB port. Alternatively, a Bluetooth enabled desktop computer may be used and placed within the wireless Bluetooth RS232 communication range which is about 20 metres in an enclosed environment.

The BCI box may be used as a mobile BCI unit. In this case, a small LCD display that mimics the computer monitor displaying the selection Graphic User Interface (GUI) is provided. The LCD display that gives the selection options as well as feedback for the BCI system is connected to the BCI box. The computer fitted with a Bluetooth RS232 communications unit is kept at a remote place and plugged into a mains power supply. The LCD display together with the Bluetooth enabled BCI box form the mobile BCI unit that accompanies the subject. The battery power requirements for such a mobile BCI system is much less because it is not required to power the computer.

The BCI system is used to control 4 main actions of a prosthetic hand that are described as the Grab, the Tripod Pinch, the Pulp-to-pulp Pinch and the Key Pinch and also to select 4 remote devices as denoted by 4 LED's. For asynchronous testing of the BCI system, the subject is required to select a randomly generated sequence of selections that consists of the 4 desired hand actions and 4 remote devices. Based on the manner the sequence is programmed, the estimated minimum time required by the subject to complete the selection of the sequence is 7 minutes. The actual time taken by the subjects to complete the selection of the sequence is recorded. The results show that the more proficient subjects take 8 minutes and the less proficient ones take up to 15 minutes to complete the sequence of selections.

**RESTORING ARM & HAND FUNCTION BY THOUGHT.**

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The primary focus of our lab is to utilize cortical signals to restore upper limb function by thought to individuals with severe paralysis. We are coordinating efforts with our colleagues at the Cleveland FES Center to link the cortical command signals to the implanted functional electrical stimulation (FES) systems that restore upper limb movements through controlled stimulation of the peripheral nerves. This also includes utilizing cortical signals to drive a robotic arm for individuals whose own limbs cannot be activated with peripheral nerve stimulation (e.g. people with ALS, or severe limb injuries or denervation).

We are developing methods to utilize cortical signals from a range of invasive and non-invasive brain recording technologies including intracortical microelectrode arrays, EEG sensors embedded in the skull, and scalp surface EEGs. Our goal is to maximize the benefit to the user from each of these technologies thus providing a range of options that all have good risk/benefit ratios.

With any of these recording technologies, it is possible that we will not be able to extract enough high-resolution, independent command signals needed to simultaneously drive all degrees of freedom (DOF) of the robotic or FES-activated limb (e.g. XY&Z position, hand orientation, finger flexion, etc.). We are working to resolve this mismatch by developing strategies that will optimize the neural information and sequentially map the available command signals to critical device functions. We are using the following approach:

1) In a distracting, realistic, virtual-reality training environment, evaluate and refine different coadaptive decoding algorithms to maximize the number of simultaneous DOF that can be extracted from the trained cortical signals. This includes converting adaptive decoders (originally developed for use with unit firing rates) into decoders that also utilize field potentials and adjust to find the most useful spectral information for control (i.e. number, range, and location of frequency bands)
2) Develop robust state detectors that can be used to change functional 'modes' (e.g. on/off, reach/grasp). So far, support vector machines appear to be the best option.
3) Develop methods of rapidly extracting reach goal information so the available command signals can be switched over to controlling hand function once the limb is set into motion.

By utilizing robust classifiers to switch between states along with separate decoders optimized for the functions needed in each state, we hope to restore reach and grasp by thought to paralyzed individuals via a range of invasive and non-invasive recording technologies.

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# BIOMEMS INTERFACES WITH THE NERVOUS SYSTEM: FROM CELL CULTURE TO CLINICAL APPLICATIONS

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The mission of the NITRO lab group is to develop state of the art technology to interface with the nervous system, apply these tools to research challenges in neuroscience, and optimize this technology for use in clinical applications. The basic tools we utilize are rooted in BioMEMS technology development to provide long-term electrical and chemical interfaces with the nervous system, in applications ranging from lab on a chip cell culture systems to implantable clinical devices. Currently our research interests are concentrated in the areas of tissue reactions to implantable devices and clinical neural prostheses. We are currently developing novel bioprinting
techniques to control the patterning of biological proteins and polymers within neural recording arrays. We are using this technology to investigate the roles of spatial and temporal delivery of trophic factors on the integration of neurons into implantable devices. In our clinical studies, we are looking at strategies for using electrocorticograms (ECoG) from human patient volunteers as a command signal for a cortical neuroprosthetic. Specifically we are investigating different cortical areas as potential neuroprosthetic implant targets. Preliminary work shows that a wide range of cortical areas can be volitionally controlled by human patients, ranging from traditional motor areas to auditory and memory regions.

**BRAIN RESEARCH AT THE NEUROIMAGING LABORATORY OF THE UNIVERSIDAD AUTONOMA METROPOLITANA**

Oscar Yañez-Suarez
Universidad Autonoma Metropolitana - Iztapalapa

Within the Department of Electrical Engineering at the Universidad Autónoma Metropolitana, Iztapalapa campus, and associated to the graduate program in Biomedical Engineering, the Neuroimaging Laboratory has devoted several years of research to brain signal and image processing and analysis techniques rooted on statistical pattern recognition.

On the imaging side, the laboratory dedicates its efforts to the design of data-driven, statistically robust segmentation and registration methods for anatomical magnetic resonance imaging. Relevant contributions in this area have been the development of an adaptive, non-parametric, density gradient – based method for unsupervised clustering, which has been successfully applied to mono-spectral images under varying degrees of noise and bias field; an intensity normalization procedure for multi-spectral stacks; and an adaptive, combined RFB-network /active-contour scheme for multi-spectral segmentation.

With respect to signal processing, handled applications in the Lab range from standard statistical brain mapping to source localization during semantic tasks under normal and pathological aging conditions. Collaboration with the Audiology Laboratory in our campus, introduced the group to the challenges of automatic identification of event related potentials, with an orientation to automated and objective hearing loss screening. A thorough psycho-physical evaluation methodology for automated screening tests has stemmed from these initial works. Following this line, recent collaborations with the Faculty of Psychology of the National University and the Faculty of Bioengineering at the Universidad Nacional de Entre Ríos, Argentina, have led the research group into the non-invasive BCI arena. In our approach to this area, we have given utmost relevance to statistical performance evaluation of different processing schemes, either coming from published work from other research groups or from the group's original strategies.

We have recently proposed to the BCI community a subject-specific electrode selection strategy based on classification efficiency analysis. Currently the group is focusing its efforts on analyzing the performance effects of both ICA and spatial PCA preprocessing for artifact removal and dimension reduction, over SVM-based classification of P300 events.

While these ongoing studies develop, our laboratory is now about to acquire a new biosignal recording system, which will be interfaced to the BCI2000 software in the near future. This will permit our first in-house experiences towards online BCI. The group is also putting some effort into the development of hardware support for the eventual realization of the most reliable classification schemes. In this regard, an FPGA-based, 16 bit fixed point pipelined linear SVM core has been developed and is currently under testing.

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**BCI RESEARCH AT THE NEURAL SYSTEMS LAB, UW**

Pradeep Shenoy, Rajesh Rao
Neural Systems Lab, University of Washington

At the Neural Systems Laboratory, we are interested in the following topics pertaining to Brain-Computer interfaces: bayesian models for user behavior and task performance, the integration of multiple sources of
information, the study of adaptive models and methods for BCI, and the study of task performance using noisy control interfaces. In previous work, we have considered the problem of estimating high-level brain
states such as "intent to move", "move left hand", etc. from EEG and EMG signals during a left-right hand movement task. Dynamic bayesian networks are a powerful tool for modelling such tasks. We have also built an EMG-based control scheme that can control a 4-degree-of-freedom robotic arm with a high degree of accuracy. In current work, we are exploring performance of more complex tasks using noisy control signals such as EMG. This is interesting and valuable because it allows us to study higher-bandwidth interfaces and the issues involved thereof, for use in future BCIs with higher information transfer rate, e.g., using ECoG. We also intend to explore the adaptive behavior of subjects using a BCI, and propose schemes via which the BCI can exploit such user adaptivity.

# BRAIN-COMPUTER INTERFACE RESEARCH AT AALBORG UNIVERSITY

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The Laboratory for EEG Analysis at Aalborg University focuses its research on quantitative methods of EEG recording and analysis for development of diagnostic and therapeutic methods and equipment. Experimental research is also conducted on respect to brain function associated to motor control with the purpose of gaining more knowledge in the perspective of rehabilitation.

Our focus on brain-computer interfaces (BCI) is so far directed towards the Steady-State Visual Evoked Potentials (SS-VEP) using a standard computer screen for stimulation. Accordingly, subjects are presented to a matrix of 3 by 3 squares, each flickering at a different frequency; thus, depending on which square the subject directs its attention it is possible to distinguish specific frequency components in the EEG signals recorded over the visual cortical area (occipital region). Feature extraction and classification are based on power spectral analysis and amplitude criteria, respectively.

This BCI based on SS-VEP appears to be a promising approach since accuracy of up to 92.8 % can be achieved with symbol signaling rate of 12 chars per minute. Besides, the required training time seems to be negligible and high detection speeds are possible, even though some control of eye movements is still needed. The current efforts on this kind of BCI are directed towards the implementation of the "multi-tap"; alphabet (like those used in text messaging of mobile phones) in connection with predictive text input in order to speed up the information transfer rate and promote an efficient communication tool for patients.

In the lane of basic research we have been investigating the cortical modulation of movement-related parameters. The aim is to enhance the control of function electrical stimulation (FES) by integrating a BCI system capable of recognizing cortical activity related to e.g. amount of force, velocity and direction desired by the patient for a determined action. The control (and command) of these parameters may be of most importance when performing complex tasks like overcoming obstacles during walking, controlling pedals (e.g. driving a car), etc. Controllers of FES systems, provided with these movement-related cortical potentials (MRPs) through BCIs, would require simpler algorithms and strategies because part of the inputs would be already pre-programmed by the patient's own preserved areas of the nervous system.

Considering the basic physical demands involved in essential motor functions associated to lower limbs, we have been studying the relationships associated to ankle plantar flexors. Accordingly, it has been possible to identify, for instance, that MRPs are function of rate of force development and force amplitude. Changes in directional orientation during gait initiation also seem to be directly modulated by MRPs mainly due to adaptations of the body geometry and muscle synergies. Moreover, the resemblance of this cortical modulation in imaginary movements has been also investigated, looking to the application of BCIs in patients which are deprived of normal neural pathways. Last but not least, motor cortical modulation is being investigated on a single trial basis with techniques of feature extraction and classification involving signal-based wavelets.

A special attention has been given to spatial distributions of both MRP intensities and statistical significant differences of MRPs between different tasks. Hence, the identification of specific scalp regions associated to variations of movement parameters may help in the optimization of BCIs by allowing reductions in the number of recording electrodes without loss of information. In that sense, customized EEG caps with high density of electrodes over the motor cortical area have been employed in those experiments related to the investigation of motor cortical modulation. Aalb. Univ, Danish National Research Found, UNIVAP

# ONE-DIMENSIONAL CURSOR CONTROL AND INITIAL STUDIES WITH TWO-DIMENSIONAL CURSOR CONTROL USING ELECTROCORTICOGRAPHIC SIGNALS IN HUMANS

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Brain-computer interfaces (BCIs) use brain activity as a new communication channel for people with severe motor disabilities (Clin Neurophysiol 113:767-791, 2002). Many BCIs use either scalp recording of EEG or extracellular recording from implanted intracortical recordings. Both have potential disadvantages. EEG has low spatial and temporal resolution, while current intracortical recording has limited long-term stability and entails significant clinical risks. Electrocorticographic (ECoG) activity recorded from the cortical surface could be an intermediate method which combines high spatial and spectral resolution, long-term stability, and lower clinical risk. Recent work has demonstrated that people can quickly learn to use ECoG signals to control cursor movement in one dimension (Leuthardt et al., J Neural Eng, 2004).

We are now extending this work by additional one-dimensional studies and by initial two-dimensional experiments in patients who are temporarily implanted with electrode grids on the cortical surface prior to epilepsy surgery. Patients perform sets of motor and imagery tasks while up to 128 ECoG channels are digitized and stored using BCI2000 software (Schalk et al., IEEE Trans Biomed Eng, 2004). This procedure yields features (i.e., signals at particular channels and frequencies) specific to actual or imagined tasks and therefore potential sources of control. Using these signals, patients control a computer cursor from the center of a screen towards targets on the sides of a screen for one- or two-dimensional control. This control is often highly spatially specific, sometimes immediate and has most often been acquired from locations in the precentral gyrus. Almost all patients (i.e., 4 out of 5) were able to rapidly obtain one-dimensional control using imagined tasks. In one of these patients, we were also successful in demonstrating accurate two-dimensional control using actual movements and imagined. Experiments with two-dimensional control indicate that, with current source isolation technique, some user training is necessary. The currently lengthy signal identification procedures and the restricted time frame that is available for patient training impede flexibility for user learning process. With further confirmation and development, these results further support the possibility that ECoG can support a powerful and practical BCI methodology.

# COULD CORTICAL SIGNALS CONTROL INTRASPINAL STIMULATORS?

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## Introduction

Recent advancements in the field of brain-computer-interface (BCI) demonstrated that this approach could be used to translate volitional signals into control commands for operating external assistive devices. It is conceivable that cortical signals could also be used to control functional electrical stimulation (FES) implants for restoring limb movements in individuals with severe motor deficits. Intraspinal microstimulation (ISMS) was suggested as a potential FES technique for restoring standing and walking after spinal cord injury (SCI). The lumbar enlargement (5 cm-long in humans), is the target region for implantation and contains motoneurons innervating all lower extremity muscles as well as large proportions of the neuronal networks involved in locomotion. By tapping into this "control center" in the cord, one can take advantage of built-in networks that generate synergistic leg movements. To determine whether intraspinal implants could be driven by volitional cortical commands, an assessment of the control signals necessary for restoring stable limb movements with ISMS was investigated.

## Methods

Experiments were conducted in adult cats that had received a complete SCI at T11 2-4 weeks earlier. Under isoflurane anesthesia, microwires were implanted bilaterally in the lumbar enlargement. Microwires targeted regions of the ventral horn that generate hip, knee, and ankle flexor or extensor movements when electrically stimulated. The cats were then decerebrated and anesthesia was terminated. The animals were transferred to a custom-built split belt treadmill with indwelling force plates, and placed in a body harness that provided partial body weight support. The treadmill belts remained stationary throughout the course of experiments. Electrical stimuli (1s trains, biphasic, charge balanced pulses, 200 μs, 2-300 μA, 40 or 50 s-1) were delivered through individual microwires and those eliciting flexor, extensor, forward or backward movements were identified. Two stimulation strategies were used to induce bilateral stepping: 1) phasic stimulation in which amplitude-modulated stimuli were simultaneously delivered through wires in one side of the cord eliciting whole-limb extension and wires in the other side eliciting whole-limb flexion, 2) tonic stimulation in which constant, low-level amplitude stimuli were simultaneously delivered through 2-4 bilaterally positioned groups of microwires. Kinematics, kinetics and electromyographic activity of the evoked stepping were documented.

## Results

Synergistic multi-joint movements of the hind limbs in cats with complete SCI were generated by ISMS through individual microwires. Amplitude-modulated (Th to 4 or 5x Th), phasic ISMS through 4 microwires in each side of the spinal cord generated near-normal bilateral, fatigue-resistant stepping. Full weight-bearing during stance and ample foot clearance during swing were achieved. Phasic stimulation required two independent command signals to produce bilateral stepping that could be adequately adapted to environmental demands. Constant-amplitude (0.9x Th to Th) tonic ISMS through groups of 2-4 bilaterally located microwires induced near-normal, weight-bearing stepping. A single command signal was needed to control this mode of stimulation.

## Discussion and Conclusion

We conducted a set of preliminary studies to investigate the efficacy of ISMS in restoring leg function after SCI and to determine the minimum number of command signals necessary to induce stepping. The findings suggest that the neuronal networks for locomotion continue to be viable after injury, and that ISMS could indeed restore functional stepping, evoke weight-bearing fatigue resistant movements, and recruit motor units in near-normal physiological order. Given that ISMS operates through the activation of coordinated networks in the ventral horn of the spinal cord, it is capable of eliciting a wide range of synergistic movements through the use of a small number of implanted wires. Depending on the stimulation strategy deployed, stepping could be restored through the use of one or two independent command signals. This has the potential to reduce the demands on cortical controllers in systems that employ BCI technology for restoring limb movements.

## COMPARISON OF PLATFORMS FOR BRAIN-COMPUTER INTERFACES

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g.tec Guger Technologies OEG

Operators of brain-computer interfaces (BCI) have a different skills due to working background. Roughly three classes of operators exist: (i) end-users, (ii) users who realize scientific applications and (iii) developers. Depending on this classification different demands for a BCI system occur. End-users are dealing with a relatively large amount of subjects and need therefore a reliable, cheap system that is easy to operate. Users who realize scientific applications need a flexible platform which allows to adapt e.g. the signal processing and classification algorithms and to exchange the experimental paradigms. Developers need direct access to the biosignal amplifier, to the signal processing algorithms and paradigms to include their own programming code in order to realize new BCI systems.

g.tec has developed a total development environment which provides hardware and software components for the different demands. For portable applications the battery powered g.MOBIlab allows to acquire data over the standard serial interface. The device can be connected to a PC, notebook or Pocket PC for portable usage. The stand-alone amplifier g.BSamp can be connected to many custom data acquisition board with analog input channels and supports already existing applications. The universal serial bus based amplifier g.USBamp can be connected to a PC or notebook without any additional data acquisition device.

The device drivers can be divided into the following categories (i) C++ application programming interface (API), (ii) MATLAB API and (iii) Simulink driver block. All three device drivers allow to read out on-line the data of the amplifiers. The C++ API can be used to create stand-alone programs which are mainly interesting for end-user systems. The MATLAB API allows to realize new applications under MATLAB and gives access to all MATLAB toolboxes for further processing. The Simulink driver block allows to realize easily real-time applications with all standard Simulink blocks.

The development time is shortest with Simulink, followed by MATLAB and then C++. The advantage of C++ is to create stand-alone applications which can be distributed to many users without license costs of MATLAB. The new MATLAB compiler allows to create also stand-alone applications which run without MATLAB. Therefore the flexibility of MATLAB can be used for the development phase and when the distribution phase is reached, a stand-alone version is created. The main advantage of the Simulink version is the speed up in the development time. New processing algorithms and paradigms can be realized within hours and tested in real-time.

At this stage of BCI research it is still important to have a highly flexible environment to adjust the BCI components and it will be the main task in the next years to find solutions which fulfil the end-user requirements.

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## SIGNAL REPRESENTATIONS BASED ON SINGULAR-VALUE DECOMPOSITIONS FOR DISCRIMINATION OF EEG FOR DIFFERENT MENTAL TASKS

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Colorado State University

Generalized singular-value decomposition is used to separate multi-channel EEG into components that optimize several different measures. These components may be used to filter out artifacts and to classify EEG according to which mental task is being performed. Examples will be presented of the filtering of various artifacts, including some generated by an ALS patient's support systems. Examples of discrimination of EEG across a set of mental tasks will also be shown.

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# A COGNITIVE NEURAL PROSTHETIC SYSTEM USING POSTERIOR PARIETAL CORTEX

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Neural prosthetic devices are being developed to improve the communicative and locomotive capabilities of severely paralyzed individuals by allowing them to control devices using only neural activity. The work in our laboratory is focused upon extracting both motor parameters, such as movement direction and velocity, and cognitive parameters, such as the movement goal and the predicted reward associated with that movement, from posterior parietal cortex. We expect that using a combination of motor and cognitive signals will maximize the potential usefulness of future neural prosthetic devices.

Recently, we have shown that signals from an area of macaque posterior parietal cortex called the parietal reach region (PRR) can be used for prosthetic control. These signals are present in the absence of any movement on the part of the subject and are spatially tuned to the goal of a planned arm movement. Importantly, movement goals can be decoded from this area very quickly (under 100 ms) and very accurately using only a small population of neurons (~ 10). Interestingly, these signals are modulated by the reward the subject expects to receive from the upcoming movement, opening up the possibility of using PRR to assess the motivational state of a subject in addition to decoding his motor intentions.

Our laboratory is also addressing the limited lifetime of electrode recordings via a two-fold approach. First, we are exploring the possibility of using local field potentials (LFPs) from PRR, as opposed to single unit activity, to decode arm movement plans. The LFP is a low frequency oscillatory signal that is comprised of summed activity from thousands of neurons and is present long after single unit activity disappears due to glial encapsulation. We have previously shown that LFPs from the intraparietal sulcus predict the direction of upcoming saccades and reaches.. Our laboratory is also developing moveable probe technology that will allow independent positioning of each electrode within an electrode array. These moveable probes are being developed in concert with algorithms that provide automatic isolation of single units on a given electrode, thereby continuously optimizing the effectiveness of the system without requiring manual adjustments on a regular basis.

One potential advantage of extracting control signals from PRR is that this area maintains sensory input after spinal cord injury, as opposed to primary motor cortex, which undergoes deafferentation and may pathologically reorganize to such a degree that it affects the ability to extract prosthetic control signals. We expect that PRR will reorganize less than motor cortex, if at all, and we are currently testing this hypothesis is in our laboratory using fMRI.

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**REAL-TIME IMAGE TRIAGE BASED ON SINGLE-TRIAL DETECTION OF VISUAL RECOGNITION AND DISCRIMINATION EVENTS IN EEG**

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We are developing a real-time EEG-based brain-computer interface (BCI) system for triaging imagery presented using Rapid Serial Visual Presentation (RSVP). A target image in a sequence of non-target distractor images elicits in the EEG a stereotypical spatio-temporal response, which can be detected. A pattern classifier uses this response to reprioritize the image sequence, placing detected targets in the front of an image stack. The RSVP task is effectively an oddball paradigm which is known to evoke the P300 response following low probability events. While ERP analysis indicates differences in the distribution of activity between target and non-target images, averaging trials precludes development of the triage interface which requires every image to be classified. Instead of using trial-averaged ERPs, we use single-trial analysis based on linear discrimination (Parra et al, 2005) to recover spatial components that reflect differences in EEG activity evoked by target vs. non-target images. We find an optimal set of spatial weights for 60 EEG sensors within a sliding 50 ms time window. A linear classifier is used since it enables the efficient solution for scalp projections describing the coupling of discriminating activity with the sensors, reflecting component source proximity and orientation. Using this simple classifier allows us to process EEG in real-time. The current detection accuracy is approximately 85%, i.e. in a sequence of 100 images we expect that after resorting images based on the detector output a target image has moved from a random position in the sequence to one of the first 15 images.

Image-based communication

An image is worth a thousand words. Current BCI's for communicaton are based on alphanumeric character selection. Our initial results with the image triage system suggest an image based BCI for communication based on pictorial symbols. We will describe our signal processing approach for single-trial analysis of EEG and report initial results of our real-time image triage interface.

Acknowledgements
This work was funded by the Defense Advanced Research Projects Agency (DARPA) under the Augmented Cognition program, the DoD Multidisciplinary University Research Initiative (MURI) administered by the Office of Naval Research (N00014-01-1-0625) and by the NIH (EB004730).

**Reference**

L. C. Parra, C. D. Spence, A. D. Gerson and P. Sajda (2005), Recipes for the Linear Analysis of EEG, NeuroImage, in press.

# SOUTHAMPTON BRAIN COMPUTER INTERFACING (BCI) RESEARCH PROGRAMME

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## Introduction

This relatively new collaborative Research Programme unites biomedical engineering and the clinical sciences, based within the Life Sciences Interfaces and Neuroscience Initiatives at the University of Southampton, providing a cohesive scientific basis for rehabilitation research and management. Projects are developing within the Programme, in different areas of rehabilitation. Current activity largely involves forming research teams to develop proposals and seek funding for specific projects.

## Aims

The overall aim is to help bridge the gap between major technological advances and the relatively limited success in practical applications of BCI to date.

Projects are driven by clinical problems, taking cutting-edge signal processing research, which aims to develop an investigative tool for advancing knowledge of neurophysiological mechanisms, whilst providing a practical therapeutic system for use outside a specialised BCI laboratory.

In terms of clinical applications, our goal is to advance the person interface (ease of use, etc.) and technological aspects (e.g. minimal recording channels, refining signal processing), to improve BCI accessibility and compliance.

## Programme Themes

The Southampton Programme broadens the approaches in BCI research by focussing on four distinctive themes:

1. Advancing BCI as a tool for scientific investigation and diagnosis, in addition to its more well established function as a communication device
2. Using BCI to elucidate neurophysiological mechanisms of normal function, dysfunction and recovery, guiding research into therapeutic interventions
3. Development and applications of signal processing techniques:
   - Continued development of Blind Source Separation based signal processing techniques.
   - Minimal EEG channels for practical implementation through dynamical systems.
   - EEG denoising techniques tracking brain activity through semi-blind source separation.
   - Comparative studies of different paradigms for specific applications allow assessment and development of techniques suited to different BCI paradigms.
4. Characteristics of person-friendly systems to widen accessibility and compliance:
   - ease of user tasks (not too skill-dependent)
   - minimal training periods
   - broad range of task options available for individual choice

## Example project areas

- Investigation of Language Impairments

A system is being developed that involves a range of tests to investigate the mechanism of language impairment and their potential ability to access BCI. The battery of tests includes neurophysiological, neuropsychological, cognitive and clinical language assessments of varying complexity.

- Comprehensive investigation of signal processing techniques

Comprehensive comparative investigation of various signal processing approaches used by different BCI research groups to assess the appropriateness of different paradigms for specific applications within BCI. This approach will form an ongoing theme of the Programme throughout its life, to keep abreast of, and maximise, advances in the field. This area requires multi-centre collaboration.

- Integrating BCI with other technologies

Studies are being developed to integrate BCI with other existing technologies to enhance diagnostic tools and therapeutic techniques in different aspects of rehabilitation and biological sciences.

**Multidisciplinary Collaboration**

This emerging Programme includes disciplines in: neuromuscular physiology, biomedical signal processing, computational intelligence, Speech & Language Therapy, medicine, physiotherapy, psychology, computer science and computer music research. Further national and international collaborations with other BCI groups are being explored to enhance achievement of the Programme's goals.

**Future Plans**

This Programme is at an early stage of development, so most of the activities and aims outlined above relate to future work. We believe the most productive approach will be to form appropriate collaborations in the BCI community that build on our relative strengths.

# BIOMETRIC INTERFACE RESEARCH AT THE GSU BRAINLAB

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The mission of the GSU BrainLab is to explore the potential of biometric inputs for communication and control, focusing on real-world applications for people with severe disabilities. We aim to facilitate quality-of-life improvement by providing alternative paths of control for people with motor impairments. The GSU BrainLab currently has ongoing projects in several BCI and assistive technology areas:

**Biometric Control Studies**

Steady State Visual Evoked Potentials (SSVEP) - In a series of pilot studies collaborating with the Wadsworth Center, we have begun to explore the SSVEP as a control signal. A major advantage of the SSVEP based system is that it does not require training. Initial results have been encouraging, as preliminary accuracy for most subjects is better than other types of BCIs for untrained subjects. We have experimented with stimulus frequencies to determine the optimal frequency pairs for binary selections. We have also tested control interfaces that do not require gaze shift to demonstrate that an SSVEP may be an independent BCI. We have begun studies to validate the SSVEP with a variety of control paradigms including a multi-choice graded control task, continuous control, and two-dimensional control. In a pilot study, we explored real-world applications, demonstrating an SSVEP-based system with an environmental control interface. We are currently performing a study to determine whether locked-in subjects can use an SSVEP-based system for communication. We are designing an extensive set of studies with both able-bodied and disabled subjects to determine the effectiveness of SSVEP for control, including testing the effects of training.

Functional Near Infrared (fNIR) imaging - In a new collaboration with the University of Virginia and Archinoetics Inc., we have begun studying fNIR imaging to implement a control interface. A pilot study imaging over Broca's area showed good results with both able-bodied and locked-in subjects. The fNIR control interface does not require training and has been up to 100% accurate in selection trials. This project has just been awarded funding and will be a major research focus for the BrainLab in the coming years.

BioGauges - In a collaborative study with the Neil Squire Society, we have created a toolkit to allow researchers to objectively measure and characterize the capabilities of a user with a biometric transducer. The BioGauges toolkit provides a series of "gauges", which are simple, instrumented control interfaces for both continuous and discrete inputs. A set of analysis tools allows the outputs of the gauges to be compared with other transducer outputs to obtain unbiased performance results. We demonstrated the BioGauges toolkit with a mu-based BCI transducer, the LF/ASD BCI transducer, and a Galvanic Skin Response transducer. Future directions include designing gauges for spatial reference (P300, SSVEP) and other continuous control (SCP) systems.

Galvanic Skin Response - We have studied the potential of Galvanic Skin Response as a control signal via a series of experiments with both able-bodied and locked-in subjects, utilizing a commercial polygraph machine. Control accuracy with able bodied subjects ranges from 60-100%, and one of our locked-in subjects has been able to spell with the system and currently uses it as his only means of communication.

**Quality of Life Applications**

P300 Robot Arm control - In order to test whether a P300 interface can be used to control a real-world device, we developed a P300 controller for a robotic arm programmed to perform the steps to make coffee. The experiment showed that users can control a P300 interface when performance feedback is given by a real-world device only (requiring the user to shift attention from the P300 stimulus interface to observe whether the correct coffee-making step was selected). We also tested concurrent and interleaved operation of the P300 interface and the robotic arm, and found that users actually perform better in the concurrent control paradigm. These results are encouraging, implying that a P300 based control interface can be used in a real-world scenario, and that the distraction of an environmental device does not significantly affect the user's performance. Future work includes adapting the P300 interface to SSVEP and fNIR control.

BrainBrowser - One of the greatest quality of life improvements for a locked-in person beyond communication is access to the internet. We have developed and pilot tested a web browser with a mu-based control interface that allows a user to surf the web with BCI control. We are currently adapting this browser for a P300 interface.

Aware 'Chair - The "Aware 'Chair" is a context-aware intelligent power wheelchair which integrates environmental control, communication, and multilevel prediction based on context and user history. The communication and environmental control systems are informed by environmental sensors, user history, time of day, medical status and other information in order to predictively narrow the selection space, thereby improving user performance. We are currently adapting the Aware 'Chair control interfaces for P300 and SSVEP control.

Neural Navigation - We are addressing the issue of 2-D spatial movement via the Neural Navigation project. We have designed and pilot tested P300-based control interfaces for discrete movement, and are currently designing a study with able-bodied subjects driving a remote-controlled vehicle. We have also fitted the Aware 'Chair wheelchair with a remote control device, and Phase II of the navigation study will employ the wheelchair itself as the object of control. We eventually plan to test the ability of users to drive the wheelchair while seated in it using neural control, employing appropriate safety mechanisms. In the future we plan to study SSVEP and fNIR control interfaces for navigation.

**Collaborations**

The GSU BrainLab currently enjoys active collaborations with researchers at the Wadsworth Center, the University of Tuebingen, Neil Squire Society, Georgia Institute of Technology, the University of California at Berkeley, the University of California at San Diego, the University of Virginia, Archinoetics (Hawaii), and the University of Buffalo. Our funding sponsors include the National Science Foundation, the National Institutes of Health, the National Institute of Disability and Rehabilitation Research, and Georgia State University.

# BCI COMPETITION III - PRESENTATION OF THE RESULTS

Klaus-Robert Müller(1,2), Benjamin Blankertz(1), Dean Krusienski(3), Alois Schlöegl(4), José Millan(5), Michael Schroeder(6)
(1) Fraunhofer FIRST (IDA); (2) University of Potsdam ; (3) Wadsworth Center, NYSDOH; (4) Graz University of Technology; (5) IDIAP Research Institute; (6) Tuebingen University

The goal of the "BCI Competition III" is to validation signal processing and classification methods for Brain-Computer Interfaces. To this end eight data sets of brain signals from BCI experiments of leading laboratories in EEG-based BCI technology have been made publicly available in the internet (http://ida.first.fhg.de/projects/bci/competition_iii/). These data sets represent a variety of different BCI approaches and pose some of the burning problems in current BCI research.

More specifically, the competition comprises the following data sets:
Data set I (Tuebingen): ECoG data, session-to-session transfer;
Data set II (Albany): P300 Speller;
Data set IIIa (Graz): multi-class problem, good/medium/bad subject;
Data set IIIb (Graz): non-stationarity problem;
Data set IVa (Berlin): small training sets, subject-to-subject transfer;
Data set IVb (Berlin): continuous test data without trial structure;
Data set IVc (Berlin): test data contains 'rest' trials;
Data set V (Martigny): multi-class, test data without trial strucutre.

In the literature many machine learning and pattern classification algorithms have been reported to give impressive results when applied (offline) to BCI data. Still it is often hard to assess objectively their relative utility for actual BCI systems. The BCI Competition has been organized to give an unbiased evaluation in this respect.

Researchers worldwide have tuned their methods to the provided 'training' data sets and submitted the output of their translation algorithms for the test data. The truth about the test data is so far only known to the lab that provided the data. It is used to evaluate the submissions. At this special session of the BCI Meeting the curtain will be lifted to reveal the winning teams of the BCI Competition III.

**BRAINGATE NEURAL INTERFACE SYSTEM: FEASIBILITY STUDY OF A HUMAN NEUROMOTOR PROSTHESIS**

Leigh R. Hochberg, M.D., Ph.D., Jon A. Mukand., M.D., Ph.D., Gerhard Friehs, M.D., and John P. Donoghue, Ph.D.

Brown University, Massachusetts General Hospital, Spaulding Rehabilitation Hospital, Sargent Rehabilitation Center, Rhode Island Hospital, and Cyberkinetics Neurotechnology Systems, Inc.

Objective: To determine the safety and feasibility of using intracortical recordings for direct control of an external device by persons with tetraplegia.

Background: The firing patterns of primary motor cortex (M1) neurons contain information about the direction, velocity, and force of movement. With advances in chronic intracortical recording technologies, several laboratories have shown that a monkey can gain direct, on-line control over an external device using only the neural signals recorded from its cortex. Because M1 remains relatively intact in spinal cord injury (SCI) and a host of other paralyzing illnesses, it is hoped that by directly linking M1 activity to a computer, persons with tetraplegia will be able to regain functional independence, first by directing an Environmental Control Unit, and eventually by regaining control of their own limbs. Toward that goal, we report preliminary results from the ongoing BrainGate Neural Interface System pilot clinical trial.

Design/Methods: Study participants to be recruited (FDA Investigational Device Exemption) must be tetraplegic for at > 1 year secondary to SCI, stroke, or muscular dystrophy; able to speak; and be medically stable. A 4x4mm array of 100 microelectrodes is implanted into the arm-hand area of the dominant M1; the array is attached to a connector that is secured to the skull and conveys the neural signals to the remainder of the BrainGate system: an amplifier, a neural spike discriminator, a decoder that converts neuronal activity into cursor command signals, and a set of flat-panel monitors. Following post-operative recovery, participants return home. About once per week for one year, participants will attempt to gain computer control using only their thoughts. Device safety will be monitored and recorded; feasibility will be determined by the ability to discriminate multiple neurons and by the participant's ability to demonstrate direct cursor control.

Results: The BrainGate device was placed in participant #1 in June, 2004. Surgery and recovery were uneventful. Multiple neurons have been recorded at every recording session since August 2004. The participant has gained control over a computer cursor. Furthermore, using a specially developed desktop and interface, he has adjusted his television volume and channel, opened simulated e-mail messages, "drawn" simple pictures, and opened and closed a model robotic hand. A new user interface using brain activated "buttons" or "switches" is under development. Additional neuronal ensemble and direct brain-to-computer results will be presented.

Conclusions: Intracortically-based brain-computer interfaces have the potential to provide improved independence, environmental control, and mobility to persons with paralyzing injuries or illnesses. The safety and efficacy of the BrainGate Neural Interface System is undergoing continued evaluation in this pilot trial. Intracortically-based electrode arrays may also prove useful in other clinical scenarios, including seizure monitoring and suppression, and rehabilitation for persons with severe motor disabilities resulting from stroke or neuromuscular disease.

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# BRAIN COMPUTER INTERFACE AT THE "TOR VERGATA" UNIVERSITY OF ROME

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There are two main research areas related to BCI at the "Tor Vergata" University of Rome: the first one is devoted to the development of faster communication devices for severely disabled people, while the second one considers BCIs as instruments to investigate brain activity.
According to the literature (Mason et al., 2003), a BCI system can be divided into two main distinct functional blocks: a transducer (TR), which is responsible to detect some sort of information from brain signals acquired with special sensors (such as EEG electrodes), and a Control Interface (CI) which translates the information detected by TRs into commands to allow subjects to interact with the environment. These two functional blocks represents distinct research sub-areas: the first one is mainly related to the development of new classifiers and processing algorithms, while the second one falls almost completely into the area of information theory and embrace fields such as message compression techniques, prediction and so on. Another important field is the one responsible of the tuning of TRs with CIs, as it affects the performances of the whole systems.

BF++, an award winning framework for the development of Human Computer Interaction and BCI systems, presented at the II International BCI Workshop (Albany 2002), deals all these aspects and provides a versatile platform to develop complete solutions on virtually any hardware and software platform. It is actually used to develop new classifiers and algorithms (such as a special class of acoustic evoked potentials, and BCI-fMRI experiments), new applications (smart virtual keyboards) and to host new platforms (such as Win64, RT-Linux, Windows Mobile 5 and 64 bit Linux) in addition to the actually supported ones (such as Win32, PocketPC, Linux, Smart phones, etc). It was written in ANSI C++ and it is has been tested with more that 20 different compilers (such as Microsoft Visual C++ 6, 7, 8 beta 2, GCC from 2.95.8 to 3.4, Borland C++ Builder 5 and 6, Microsoft Embedded Visual C++ 3 and 4, etc..). Moreover, a new set of small applications, called "BF++ Toys", are responsible to simulate different TRs and CIs performances and are able to predict which TR and CI combination represents the best solution in a specific context. They provide also some metrics relative to either TRs or CIs and are available with full source code at the author' Web Site (http://www.luigibianchi.com/bci.htm).

As for the second main research areas, the one that considers BCIs as valuable new instruments to explore brain function, a new research line was activated in order to realize BCI systems that can be used in simultaneous EEG-fMRI recording sessions: one can think to use EEG to drive some sort of feed-back to the user while collecting fMRI data, in order to investigate which brain areas activate during for example 1-D and 2-D cursor control task. This is a promising new frontier in the BCI scenario which could allow realizing "motor control tasks" experiments without the need for moving any part of the body. However, putting together EEG and fMRI devices has major drawbacks, mainly due to the artifacts that are mutually induced by the two devices: in particular EEG signals are heavily contaminated by the pulse MRI sequence artefact (PSA), induced by magnetic gradient switching into the MRI scan, and by the ballistocardiogram artifact (BCA), determined by small electrodes and wires movements related to cardiac activity. One research line in "Tor Vergata" University in cooperation with the "Enrico Fermi Center" (Rome) is actually dedicated to find the best artefact removal methods that are able to work in near real-time. Satisfactory methods have been developed to remove PSAs in general and BCAs in some protocols. However, further improvements are necessary to allow the execution of the majority of BCI experiments into the MRI scanner, a target that will be pursued in cooperation with Seung Schik Yoo at Harvard University and with the "Enrico Fermi Center".

**WIRELESS NETWORK BETWEEN THE BRAIN AND INJECTED MUSCLE-NERVE STIMULATOR/SENSORS**

Joseph H. Schulman
Alfred Mann Foundation

The Alfred Mann Foundation is developing a 64 channel battery powered brain interface implant with two-way radio telemetry that is mounted in the skull under the skin. The brain interface consists of a skull mounted implant which is connected to a very flexible thin lead to a group of 128 electrodes mounted in the brain. Versions of this system with sensing only, stimulation only and combined sensing and stimulation are being developed. The stimulation is programmable with high resolution between 5μa and 20 ma, 7μsec and 2 msec and between 1pps and 5000 pps with programmable features such as ramping, bursting and delays. The sensing voltage amplifier has a programmable gain, hi pass and low pass frequency filtering. Its input noise reference level is less and 10 μv peak. Each channel can be programmed to be unipolar or bipolar to any of the 128 electrodes. The system includes a powerful microprocessor to reduce the data to useful amounts. The battery-powered injectable stimulator/sensors are one channel each, with the same sensing and stimulating features as the brain interface. They also can sense pressure (10 to 900 mmHg ± 0.5 mmHg), distance between any two implants (1 cm to 20 cm with 1mm accuracy), and temperature with ± 0.5 °C accuracy.

Funded by the Alfred Mann Foundation

## BRAIN-COMPUTER INTERFACES CONTROLLED BY EEG, ECOG, AND MEG SIGNALS AND THE BOLD-RESPONSE IN HEALTHY PARTICIPANTS AND NEUROLOGICAL PATIENTS

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Over the past years we have developed several BCIs and tested most of them with patients in the field. Our main goal has been to provide severely paralyzed patients with a communication device and to this end, we have trained more than 20 severely paralyzed patients in BCI use. Currently, we are running brain-computer interfaces (BCIs) on the basis of the electrical activity of the brain recorded non-invasively (EEG) and invasively (ECoG), on the basis of the magnetic activity of the brain (magnetoencephalography, MEG) and of the BOLD response (real-time functional magnetic resonance imaging) with healthy participants and neurological patients. We showed that all the involved brain signals can be brought under voluntary control when participants are provided with feedback.

To compare different EEG signals we are conducting a feasibility study with patients diagnosed with amyotrophic lateral sclerosis (ALS) in a within subject design*. All patients are trained at home with the slow-cortical-potential-, sensorimotor-rhythm-, and P300-BCI. First results indicate that the BCI based on regulation of sensorimotor rhythms is feasible for most patients which is not the case for the BCIs based on the other EEG features. To investigate the interaction between BCI training and psychosocial variables we are assessing current mood and motivation before each training session and quality of life and available reinforcers after each training block*. First data indicate great variability between patients and training blocks. We are again starting long-term training with patients to establish use of an application in daily life. One such application currently used by two of our patients is a browser to surf the internet.

Brain signals related to motor imagery recorded directly from the cortical surface in epilepsy patients indicate that an accuracy high enough to control a spelling program can be achieved within one training session**. A completely locked-in ALS patient, however, has not achieved ECoG control. (This patient gave informed consent to surgery by modulation of salivary pH.)

In a study with healthy participants, we are investigating the feasibility of auditory sensorimotor rhythm feedback to acquire reliable BCI control. Auditory feedback is required for patients who have lost eye movement. In such locked-in patients it is difficult to judge their alertness. Thus, we are conducting a study on the sleep-waking cycle and daily alertness in ALS patients. To know more about alertness in severely impaired patients is directly important for BCI use because attention is needed to control any BCI and indirectly, because a good quality of night time sleep is important for a good quality of life. Quality of life is in turn linked to feelings of depression and depression hampers executive functioning and thus, may affect BCI use. Consequently, we are also investigating coping in ALS patients. Using a longitudinal study design, factors such as quality of life, social network, coping strategies, fear of death, and depression will be assessed 3 times within a year. Additionally, we will investigate cognitive and emotional processing in daily situations of ALS patients. By investigating alertness and mechanisms of coping in ALS patients we hope to elucidate how these factors influence acquisition and maintenance of BCI control.

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*In collaboration with Dr. J. Wolpaw and colleagues at the Wadsworth Center, New York State Department of Health, Albany, NY 12201-0509, USA.

**In collaboration with Prof. W. Rosenstiel and colleagues at the Wilhelm-Schickard-Institute for Informatics, University of Tübingen, 72076 Tübingen, Germany and C.E. Elger, Hospital of Epileptology, University of Bonn, 53105 Bonn, Germany.

**DASHER - AN INFORMATION-EFFICIENT WRITING SYSTEM**

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Dasher is a user interface for text entry, targeted at users unable to use a conventional keyboard. Dasher is controlled by continuous gestures, conveyed for example by mouse, joystick, head-tracker or gaze-tracker. It can also be driven by button-presses. Dasher uses a language model to make efficient use of the user's gestures. Invented in our research group in 1997, Dasher has developed into a mature open-source software application, and has many users including, for example, suffers of motor neurone disease. We believe that variants of Dasher may be well-suited for use with BCI systems, since it makes efficient use of the typically low bit-rate data from the user, and we are seeking collaborations with BCI researchers.

Users writing with Dasher are presented with a visual landscape of letters arranged down the right-hand side of the screen. To write the word “hello”, the user points or steers in the direction of the “h”, causing the display to zoom in on that region. Within the “h”, another alphabet of letters appears, allowing selection of the second letter, “e”, and so on. The amount of the display devoted to each each letter is determined by a language model. The right-hand side of the screen can be thought of as containing all possible sequences of text, laid out in alphabetical order. The user simply zooms in on the phrase they wish to write.

Dasher uses a language model, trained on text in the appropriate language and dynamically adapting itself to the user's writing, to estimate the probabilities of different sequences of letters, given those that the user has just written. Letters on the screen (and, implicitly, words and phrases) are given a size proportional to the probability that the user will wish to write them next. Thus, probable phrases are quick to write, with minimal user input. Improbable phrases (mis-spelled words, or gibberish) are always possible to write, but require more zooming, and hence more time and effort, from the user. Dasher implements the inverse of the arithmetic coding data compression method: it translates small gestures (short bit sequences) from the user into probable text strings.

The original Dasher interface is driven by a cursor (mouse pointer) with two degrees of freedom, such as may be controlled with a mouse, stylus, head-tracker or gaze-tracker. The up-down axis is used to point towards regions of the landscape to zoom into; the left-right axis is used to control speed or to reverse. After an hour of practice, subjects using a gaze-tracker were able to write at 25 words per minute using Dasher, compared to only 15 words per minute using an on-screen keyboard. They also made fewer errors, and reported that the experience was less stressful.

Dasher also has a one-dimensional mode, in which both direction and speed are mapped into a single continuous input axis. We have developed a “breath mouse” to drive this mode. Dasher can also be operated using one, two or three binary switches. In a BCI application, it would be possible to use visually-evoked responses to determine which region of the “landscape” of letters the user wishes to zoom in on.

Dasher currently allows its users to write efficiently using any muscle. Working with the BCI community, we hope to bring the benefits of Dasher to people unable to make any controlled physical movements at all.

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# TOWARDS A ROBUST BCI: ERROR POTENTIALS AND ONLINE LEARNING

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We have recently shown that after a few days of training, subjects are able to control a miniature robot in an indoor environment with several rooms and corridors using mental commands derived from an EEG-based BCI. Key aspects that make it possible are the use of an asynchronous BCI and the combination of the user's high-level commands with advanced robotics that implement those commands efficiently. We are trying to improve this initial demonstrator, in collaboration with several European institutions, along 4 lines. The first one is the development of a more powerful adaptive shared autonomy framework for the cooperation of the human user and the robot in achieving the target. The second line is the use of a technique recently developed by Grave et al. (2004) that estimates the local field potentials (LFP) in the whole human brain from scalp EEG. Recent results show significant improvements in the classification of bimanual motor tasks using estimated LFP with respect to scalp EEG (Grave et al., 2005). The third and fourth research avenues seek to improve the robustness of a BCI and will be the focus of our presentation.

Due to the nature of brain signals, BCIs will always makes mistakes in recognizing a subject's intent. However, embedded in the EEG signals there is information that provides a way of minimizing the impact of these errors. Previously it has been established that when a subject becomes aware of a mistake there is a signature in the brain, called an error-related potential (ErrP). We have now shown that this ErrP is also detectable when the error is made by the interface – i.e., the user has done everything correctly but the BCI has misinterpreted the command. This "Interaction ErrP" was demonstrated in experiments with four healthy subjects participating in a simple human-robot interaction task (bringing a robot to either the left or right side of a room). The Interaction ErrP was satisfactorily detected in single trials using the short time window following the feedback. We also show that the integration of this Interaction ErrP in a BCI, where the detection of an ErrP following feedback blocks the execution of the command, yields significant improvements in the bit-rate of the BCI.

In addition, for a BCI to be a truly effective tool it must have the ability to adapt dynamically throughout its use. The EEG signals received by the BCI will always change over time, both within a single session and between sessions, due to a number of factors. However, adapting the BCI must be undertaken with great care – rapid changes in the classifier will confuse the user, and inappropriate adaptation will be catastrophic for the classifier. Another issue that must be considered is that when feedback is provided to the user while training the classifier, there will be a mutual learning process as the user and the classifier try to adapt to each other. To facilitate this process we would like the classifier to be changing in a reasonably stable and predictable manner to allow the user to adapt as the classifier changes. We have been investigating various gradient-descent based learning algorithms that can be applied to our Gaussian classifier in an online manner. One such method is stochastic meta-descent (Schraudolph, 1999), which accelerates training by using local learning rate adaptation. Imposing a smoothness constraint on the algorithms has produced good experimental results on artificial data, and initial results on real BCI data are promising.

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# ON MRP AS A DRIVING INPUT FOR ASYNCHRONOUS BCI

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Why use Movement Related Potentials (MRPs) to drive a Brain Computer Interface (BCI) system? MRP signals can be recorded spontaneously with EEG electrodes either when a subject performs a voluntary movement or imagines such a movement. In the latter case the signal amplitude is smaller. This is the strongest feature of MRPs as no training is required, and hence a BCI based on MRPs offers a major advantage over most existing BCIs in that it operates asynchronously.

The major drawback of MRPs is their low Signal-to-Noise Ratio (SNR) compared to other Evoked Potentials (EPs). A typical SNR for MRPs is -15[dB], as compared to 0 to -5[dB] for the P300 signal. It should also be noted that such MRP signals are recorded mainly during finger movement and that MRP SNR decreases when one performs movements with more proximal joints.

It is therefore clear that the use of MRPs as a research tool or a BCI driver depends on the ability to improve the SNR to the point that one can select the proper signal features in order to classify between movements.

In our laboratory we have spent the last ten years attempting to improve single-trial MRP Signal to the ongoing EEG Noise Ratio and to develop tools for feature selection and feature classification according to movement.

One approach to improving SNR in EPs includes various parametric estimators which usually require signal-to-noise of 0[dB] or better to obtain high quality estimations. A Robust-Evoked-Potential-Estimator (REPE) [1] was developed, based on the well known Box-Jenkins model, which enhances an ARX model [2], to support low SNR signals. The REPE is capable of improving signals with an initial SNR ranging form -10 to -20[dB] by 18 to 23[dB], resulting in much improved single-trial estimations of MRPs.

The next step towards a MRP-based BCI requires developing a movement classifier. Feature extraction and selection are major difficulties when designing a classifier.
A feature selection method was developed, to choose a small number (10-20) of relevant features from a bank containing 1000 extracted features. This method is based on the use of genetic algorithms. With this method, applied to data recorded from five subjects, we were able to differentiate between movements of two limbs with a classification accuracy of 87% using as little as 10 features without subject training.
With the addition of a simple coding scheme, this method can be applied to multiple limb classification and a 63% classification accuracy rate can be reached when classifying between three limbs. [3]

Recently, a P300-based BCI was developed and tested, with results published in [4].

In the latest study in the lab related to BCI, the focus was on gamma-band activity (28-40Hz) within the signals, known to be associated with attention and voluntary motor tasks. In this study, gamma-band power and time-domain predictive features serve as two separate dimensions of input into a Brain Computer Interface (BCI) device.
Time-domain features, taken 360ms prior to motor response, were used to classify between single-trial movement and non-movement segments, resulting in 72.3% accuracy. Frequency-domain features, based on spectral power of signals estimated with the multitaper method, were used to classify between single-trial left and right movements, resulting in 75.7% accuracy. All classification was done using

Support Vector Machines. Thus, when applying these signals to a BCI device, time-domain features predict intent to initiate movement and gamma-band power features determine laterality of desired movement.


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# THE NEUROCHIP: A FULLY IMPLANTED BRAIN-COMPUTER INTERFACE FOR PRIMATES

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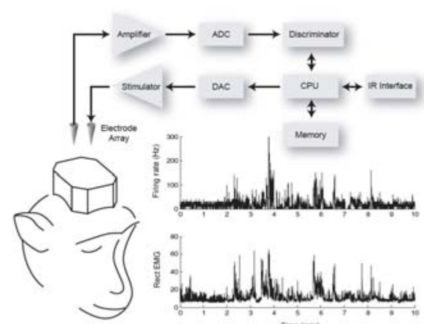
Research in our laboratory focuses on the neural circuitry involved in executing arm and hand movements. By recording spiking activity from a variety of cortical and spinal neurons in awake primates performing motor tasks we can infer the contribution of different cell types to movement (1). We have recently become interested in integrating a brain-computer interface into motor circuitry by converting cortical cell activity to stimuli delivered elsewhere in the system. Toward that end, we need to be able to (i) obtain long-term, stable, movement-related neural recordings in unrestrained primates, (ii) reliably detect and convert cell activity to control microstimulation of another part of the motor system, and (iii) condition patterns of neural activity to facilitate the incorporation of these artificial connections into normal motor behavior.

In collaboration with the Jaideep Mavoori in the Department of Electrical Engineering at the University of Washington, we have developed a miniature computer (the 'neurochip') which can be attached to the skull of primates (2). Neural recordings are obtained using a moveable microwire array chronically implanted in primary motor cortex, and differential EMG signals are recorded from wires implanted in arm muscles. Once configured by infrared link, the neurochip can operate autonomously, discriminating unit action potentials and storing spike rate and up to four channels of EMG while the animal moves freely about his home cage. Power consumption is low and with a daily battery change we can follow isolated single-units continuously for several weeks at a time, providing insight into the relationship between cortex and muscle during a range of natural behaviors. The implant also incorporates a circuit capable of delivering biphasic current pulses for microstimulation. The neurochip can be configured to deliver stimuli to one microwire triggered by action potentials discriminated at another site. We are currently investigating the effect of long-term operation of artificial cortico-cortical connections.

In related experiments, we are studying movements evoked by microstimulation of the spinal cord. Using a conventional microelectrode drive and recording chamber covering the lower cervical segments, we made repeated electrode penetrations in anaesthetized animals to map the responses to stimulation. We find that a range of arm, wrist and finger movements can be elicited, often involving synergies of multiple muscles. We hope in the future to use these results to aid the placement of indwelling electrodes for stimulation controlled by the neurochip. In this way we intend to create artificial cortico-spinal connections which could form the basis for a neural prosthesis to restore function following spinal cord injury.

Work is also underway to create artificial connections between cortical neurons and muscles with the goal of restoring movement after peripheral nerves are blocked. After operantly conditioning monkeys to control discharge rates of single cortical neurons, we plan to use these neurons to control the electrical stimulation of muscles. Use of the neurochip will permit monkeys to practice with these artificial cortico-muscular connections for extended periods and during free behavior.

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## RESEARCH IN THE STEIN LAB AT THE UNIVERSITY OF ALBERTA, CANADA

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The research falls into two categories: 1) development of methods in cats to study the role of sensory feedback for motor control and 2) studies on improved systems for assisting people with motor disabilities that combine electrical stimulation and bracing. We have implanted microelectrode arrays (Cyberkinetic LLC) in L6 and L7 dorsal root ganglia in cats. In acute experiments up to 100 units simultaneously were recorded from 100 electrodes (Stein et al., 2004, *J Physiol* 560, 883). Some units were highly correlated with whole limb position and combining even a few of these units provided an accurate representation of the position of the foot in space. Muscle receptors from double joint muscles were particularly informative. Furthermore, data collected from random movements produced by a robot predicted walking-like movements and center-out movements with an accuracy of 1-2 cm. We are extending these studies to chronic recordings using 9x4 electrode arrays in the L7 dorsal root. Two behavioral paradigms are used: cats walking on a treadmill and standing on a platform that can be suddenly rotated in pitch and roll directions. Typically, we record 20-30 units in the first week after implantation, but the number of units steadily declines with time over the course of a month. Post-mortem, histochemical examination indicates a ring of connective tissue about 100 μm in thickness with few neurons in the neighborhood of the electrodes. We are also analyzing the possible infiltration of neurotoxic cells such as microglia. Many recorded cells are rhythmically active during locomotion and their activity can predict where in the step cycle the foot is (Weber et al., poster at this meeting). The accurate prediction arises at least in part from the high correlation among some kinematic variables in joint and end point spaces (e.g., hip angle and orientation of the foot with respect to the hip). Analysis on the balance platform is less advanced, but some cells are well tuned to the direction of the rotation. One hypothesis is that cutaneous receptors in the foot are particularly important for this task (see Johansson & Birznieks, 2004, *Nat Neurosci* 7, 170).

A focus of the human studies is the condition of foot drop that is common after a number of CNS lesions (stroke, spinal cord injury (SCI), multiple sclerosis, head injury). A novel foot-drop stimulator (WalkAide) has been developed that measures the tilt of the leg and uses that signal in a rule base of a microcontroller to regulate stimulation of the common peroneal nerve (Stein, 1998, U.S. Patent #5814093). This nerve innervates muscles that dorsiflex the ankle so that the foot drop is eliminated or reduced. Hanger Orthopedic Group will be selling a commercial version in the near future. Clinical trials to date indicate that the device is well accepted, walking speed and distance are increased and the required effort is decreased (Wieler, 1999, *Arch. Phys. Med. Rehab.* 80, 495; Stein et al., 2005, *Int. FES Soc. meeting*, Montreal, in press). Additional clinical trials are planned to study benefits of introduction soon after a stroke, when patients are usually fitted with an ankle-foot orthosis. In one person to date BIONs have been implanted to obtain a more balanced dorsiflexion (Weber et al., 2004, *Can J Physiol Pharmacol* 82, 784). Systems are also under development for people with complete SCI that combine advanced braces and a walker with electrical stimulation of relevant muscles. Our goal is to build on success with relatively simple systems and work toward the more complex systems that people with more severe motor problems require.

Supported by CIHR and the Christopher Reeve Paralysis Foundation

**THE UTILITY OF HIGH GAMMA BAND (80-250 HZ) ACTIVITY IN THE HUMAN SUBDURAL ELECTROCORTICOGRAM FOR BCI COMMUNICATION AND CONTROL**

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The lab of Robert T. Knight at the University of California, Berkeley, uses scalp electroencephalography (EEG), subdural electrocorticography (ECoG), and functional magnetic resonance imaging (fMRI) to investigate the neurophysiology of attention, language, and prefrontal regulation of cognition, emotion, and action. The lab is now moving into BCI research as well. Most BCI studies focus on either 1) invasive multi-unit recording of action potentials from cortical neurons in non-human primates and rats, or 2) noninvasive recording of human EEG. The task-related high frequency power modulation seen in the human subdural electrocorticogram (ECoG), however, suggests that this high gamma band (80-250 Hz) ECoG signal may prove useful for BCI communication and control. Such high-frequency power modulation is unavailable to scalp EEG or conventionally-recorded spike-based BCI systems. In addition, since high gamma band power modulation is spatially constrained and well-predicte!
d by sensory, motor, or cognitive task demands, the need for extensive user training may be substantially reduced. Our primary BCI research objective is to investigate the utility of the ECoG high gamma band for real-time BCI communication and control.

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# REMAPPING MOTOR CONTROL

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The issue of how the Euclidean properties of space are represented in the nervous system is a main focus in the study of visual perception, but is equally relevant to motor learning. The goal the studies that I will present is to investigate how the properties of space guide the remapping of motor coordination. Subjects wore an instrumented data glove that recorded the motions of the fingers. Signals generated by the glove operated a remotely-controlled endpoint: a cursor on a computer monitor. The subjects were instructed to execute movements of this endpoint with controlled motions of the fingers. This required inverting a highly redundant map from fingers to cursor motions. We found that 1) after training with visual feedback of the final error (but not of the ongoing cursor motion), subjects learned to map cursor locations into configurations of the fingers; 2) extended practice of movement led to more rectilinear cursor movement, a trend facilitated by training under continuous visual feedback of cursor motions; 3) with practice, subjects reduced motion in the degrees of freedom that did not contribute to the movements of the cursor; 4) with practice, subjects reduced variability of both cursor and hand movements; and 5) the reduction of errors and the increase in linearity generalized beyond the set of movements used for training. These findings suggest that subjects not only learned to produce novel coordinated movement to control the placement of the cursor, but they also developed a representation of the Euclidean space upon which hand movements were remapped.

**MODELING MECHANISMS OF BIOLOGICAL CONTROL OF EEG RHYTHMS**

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While the exact etiology and biological functions of macroscopic brain potentials that reach the scalp of humans and can be recorded as the electroencephalogram (EEG) are unknown, increasing evidence and modeling efforts suggest that far from representing only the distant “roar of the crowd” of cortical neurons, EEG activities, and notably oscillatory activities, play roles in the production of optimally coordinated behavior by biasing the timing of cortical communication, both within and between brain areas.

“Closing the [brain] loop” by providing near-immediate sensory feedback about one's own EEG rhythms has long been feasible, and was popularly advocated by some 30 years ago for relaxation and altering mental state, Today, research, experimentation, peri-professional practice in this area is again increasing in at least three directions. First, the field of brain-machine interface (BMI), brain-computer interface (BCI), or brain-accuated control (BAC) system design, the focus of this meeting, is attracting widespread interest from both rehabilitation specialists and engineers. Second, a growing number of unlicensed practitioners of “neurofeedback” therapies claim to be able to treat a wide range of physical, mental, emotional and behavioral conditions, though with little formal medical research to back up their claims and observations and less understanding of the biological mechanisms involved. Finally, there are continuing efforts to use EEG feedback for mental state monitoring in transportation and other work places. Proposals range from monitoring the emergence of subject drowsiness during long pilot work shifts to near-instantly reading out early target-related brain responses during rapid image presentation.

Our laboratory is currently investigating the application of independent component analysis (ICA) to the design of BCI, mental monitoring, and/or neurofeedback interfaces. While most current studies involve the feedback of frequency information from one or two EEG channels, we propose a system where feedback delivers time/frequency information from independent components of the EEG. The signal at a single electrode represents the summation of many different sources of brain activity. Therefore, to control the signal recorded at a single electrode, one may have to control the activities of multiple cortical sources. In contrast, independent components account for the contributions of an isolated cortical source to the entire set of scalp electrodes.

We are particularly interested in testing whether such feedback may improve overall task performance, in particular during expert monitoring and learning. Such improvement might be expected if the independent component process variables controlled are involved in or, more broadly, are controlled by brain systems that regulate cognitive processes involved in optimum performance, for example attention and working memory. We have built a simple neurofeedback paradigm, currently based on the Wolpaw-lab BCI2000 software, to test this hypothesis, and are currently running pilot experiments to refine our experimental procedures. We believe that these experiments can also address fundamental questions about control of cortical EEG. Is it possible to learn to control a single independent EEG component without affecting the activities of other components?

A new form of ICA decomposition, log spectral ICA, reveals that discrete frequency bands in limited sets of independent EEG components are under common modulatory control during cognitive task performance. Applying this form of analysis to EEG data recorded during successful BCAI or neurofeedback should tell us whether subjects use the same modulatory processes to control their brain rhythm during feedback. This will bear on the fundamental relationship between macroscopic EEG activities and distributed cortical arousal and control systems.

Funded by The Swartz Foundation, US Navy

# BCI RESEARCH IN FINLAND

Laura Kauhanen, Janne Lehtonen, Tommi Nykopp, Pasi Jylänki, Jukka Heikkonen and Mikko Sams
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We have been in the field since 1998. We were partners in a EU-funded project by Adaptive Brain Interfaces during 1998-2001. Academy of Finland has funded our project On-line Adaptive Brain-Computer Interface during 2003-2005. We are also a partner in an EU-funded project Non Invasive Brain Interaction with Robots - Mental Augmentation through Determination of Intended Action. Currently, our team consists of two senior researchers, three PhD students and two undergraduate students.

In our online EEG-based BCI, artificial neural networks are used to recognize and classify brain activation patterns associated with real and attempted movements. We also work on offline analysis of magnetoencephalographic (MEG) signals, which are more localised than EEG signals. The 306-ch MEG device we are using allows simultaneous measurements of EEG.

We have examined classification of single MEG trials in five subjects (Kauhanen et al., in revision). Classification accuracy of the left vs. right finger movements was 80-94 %. Classification accuracy was quite similar as obtained in previous comparable EEG studies. The good spatial resolution of MEG probably becomes advantageous in multicategory classification, when multiple tasks involve activity in quite distinct brain areas. In addition, we have investigated the sensorimotor cortical activity of tetraplegic patients using both MEG and EEG. Preliminary results demonstrated 20-Hz sensorimotor cortex activity with both EEG and MEG, which desynchronised bilaterally during the attempted movements. Descynhronization was not followed by a “rebound”, typically seen in healthy controls. In addition, slow contralaterally-dominant movement-related potentials were detected during attempted movements. In one subject, the latter could be classified at 80% accuracy.

Dynamic information processing studies have focused on three issues: 1) the non-stationarity of the electromagnetic brain activity, 2) asynchronous detection of the onset of a finger movement and 3) investigation of a feature space formed by real-time source localization algorithms. We have developed dynamic classification using particle filters. Dynamic classification enables the classifier to follow changes in the feature space caused by the non-stationary nature of the brain activity. The use of dynamic classification using temporal features has increased classification rates in both healthy and tetraplegic subjects. We also study classification using spectral features formed when tracking EEG/MEG with Kalman filters. For asynchronous detection we are developing dynamic change-point detection algorithms to detect changes in the rhythmic activity during finger movements. These methods help to pin-point the onset of the finger movement. In the classification based on on-lin!
e source localization there are two aims: development of robust and computationally efficient inversion algorithms and tracking of localized activity using dynamic models.

We have developed a MATLAB-based BCI platform that can be used for both online and offline research. It has a graphical user interface for fast and easy handling of subject information, recordings and model building. A program that transfers EEG data to MATLAB in real time has been developed. We have tested functionality of the design in an online experiment in which subjects performed cued finger extensions every two seconds. An average classification rate of 73,5 % for four subjects was achieved. This research will be extended to paralyzed subjects performing attempted finger movements.

Future directions: 1) Neurocognitive structure of BCI use; 2) Cortical plasticity of tetraplegic patients; 3) Asynchronous detection of movement onset; 4) Real-time source localisation algorithms

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**BRAIN COMPUTER INTERFACE AT THE ENRICO FERMI CENTER IN ROME**

Girolamo Garreffa, Bruno Maraviglia
Enrico Fermi Center

The Enrico Fermi Center in Rome is a new research institute of which the famous Italian physicist Antonino Zichichi is the president. Several project in the field of applied physics are directed inside the institution and one of the most important one is that related to "magnetic resonance and brain function" were Girolamo Garreffa is the project leader. Different research lines are developed in the project, dealing with the possibilities that MR techniques offer for the study of human brain activity. A recent new approach on multimodal imaging was the opportunity to evaluate the original and concrete perspectives that BCI techniques and methods may provide in the context of simultaneous EEG/fMRI employ. In this way a new research line inside the project is just born and is just characterized by BCI research activities that are performed in collaboration with the University of Rome Tor Vergata and the Harvard Medical School (Seung Schik Yoo, Walid Kyriakos).

The Enrico Fermi Center institution has a strong cooperation with the NMR research group directed by Prof. Bruno Maraviglia at the physics department of University of Rome La Sapienza.

Further information about Enrico Fermi Center is available on the web site WWW.centrofermi.it .

Funded by The Enrico Fermi Center

# BCI CONTROL FOR LOCKED-IN PATIENT IN REAL WORLD ENVIRONMENTS

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We are working with a 52-year-old locked-in woman with ALS. Using differences in the frequency domain, we are differentiating between mental states, allowing this woman to communicate yes / no answers. We explored the possibility that using a metal pin through the skull would amplify the underlying neural signal creating a breach rhythm that could be used to gain a higher SNR and spatial resolution. An fMRI was used to determine active regions of the brain and the Broca's region was selected for its high intensity during naming tasks. Four weeks after surgery, standard 16 electrode EEG showed low amplitude and did not show any obvious breach rhythms, however. Further testing is being done to determine what benefits the pin might be providing the BCI control system.

Since this system is for the patient's use while not participating in research, several real-world issues involving EEG recording / control needed to be addressed. We found that without an active EEG system, line noise was a problem (sometimes sporadic) even when electrode impedances were ~1K. We also needed to address portability issues. To this end we developed a prototype of an active EEG electrode circuit that is embedded in wearable earphones which attaches to 3 EEG leads. The output from this circuit it sent to a USB DAQ and onto a computer. The hardware is low cost, portable and resistant to noise.

Feature extraction on the signal is initialized by a calibration session where the user is asked to participate in paradigms. The EEG signal is recorded along with the "mental state" the user is asked to put their mind in. The PSD of a sliding window is calculated during each of the mental states and then averaged. Using the differences between the "Steady State" and the other mental state(s) the algorithm determines to what degree changes in each individual frequency bins indicate a given mental state and are used to form a filter. During on-line control, the PSD bins of the on-line EEG signal are multiplied by this filter then summed. The output is a single feature that indicates to what degree the incoming signal matches an individual's calibrated mental state.

System parameters are determined by automated offline analysis of recorded data while varying window lengths, signal processing techniques and other items. The results are used to find optimal methodologies for the patient and signal.

Early on-line control results are encouraging, although issues with line noise and patient health sometimes hampered progress. In early tests caregivers indicated an ability of the patient to answer questions the patient knew the answer to with 80% accuracy, although more analysis and testing needs to be done.

Although early results had slow information transfer rates, no other form of Yes / No communication is currently working for the patient. Since the system adapts to the frequency response of each individual user, it shows marked improvement of other systems that simply band pass, sum (and possibly invert) the PSD of a signal to achieve system output. These studies are ongoing.

# THE BERLIN BRAIN-COMPUTER INTERFACE: EEG-BASED COMMUNICATION WITHOUT SUBJECT TRAINING

Benjamin Blankertz[1], Guido Dornhege[1], Matthias Krauledat[1], Klaus-Robert Müller[1,3], Volker Kunzmann[2], Florian Losch[2], Gabriel Curio[2]
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The Berlin Brain-Computer Interface (BBCI) project is a tight cooperation of neurologists and data analysts. Key features of the BBCI system are the use of well-established motor competences as control paradigms, high-dimensional features from 128-channel EEG and advanced machine learning techniques. In our first experiments we demonstrated that very high information transfer rates can be achieved using the lateralized readiness potential (LRP) when predicting the laterality of upcoming left vs. right hand movements in healthy subjects. A more recent study showed that the LRP is similarily accompanying phantom movements in arm amputees, but the signal strength decreases with longer loss of the limb. A study evaluating the effectivity of LRP based classifications in amputee patients in feedback experiments is planned for the near future.

In a complementary approach oscillatory features are used to discriminate imagined movements (left hand vs. right hand vs. foot). In a recent feedback study 3 healthy subjects with no or very little experience with BCI control achieved an information transfer rate above 35 bits per minute (bpm), and further two subjects above 24 and 15 bpm, while one subject could achive no BCI control. These results are encouraging for a EEG-based BCI system 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 with other BCI systems.

Finally we would like to point out that the BBCI system is not resticted to establish an EEG-based control. Rather it encompassed, e.g., techniques to estimate mental workload of a subject engaged in cognitive tasks. This application was successfully demonstrated in a real-world feedback study with 13 subjects.

## DEVELOPMENT OF A HUMAN NEUROMOTOR PROSTHESIS

John P. Donoghue, Arto Nurmikko, and Michael Black
Brown University and Cyberkinetics Neurotechnology Systems, Inc.

The ideal human neuromotor prosthesis (NMP) will restore complete independence and mobility to persons with severe paralysis by using innate cortical movement signals to [3]reconnect[2] brain to limb(s). In the first stage of the BrainGate trial, an externalized connector conveys these signals to a computer-based decoder, and relatively simple decoding filters are being used to convert motor cortical commands into effector control signals. Ongoing studies at Brown University seek to develop a fully implantable, optically-connected NMP which can harness more effective decoding algorithms that can help to provide useful devices.

In the Nurmikko laboratory, the focus of research is to integrate ultralow power integrated circuit chips directly on the multielectrode neural recording element for a monolithic, compact, brain-implantable device. The microelectronic chip will enable neural signal amplification and processing in-situ, before the information is converted to a digital optical data stream which is carried from the brain by an optical fiber. The optical fiber is telemetrically coupled to outside the patient, e.g. from the abdominal cavity. To date, we have demonstrated a viable microelectronic chipscale neuroport, as well as developed the components required for the fiber optic-based neural signal "information superhighway".

In the Black laboratory, statistical learning and probabilistic inference techniques are used to infer the hand position of a nonhuman primate from multi-electrode recordings of motor cortex neural activity. We are working on algorithms and control methodologies to allow direct connection of the central nervous system to robotic devices, in particular to restore lost function. Currently, our main focus is on building and exploiting richer, more representative probabilistic models than those used, for instance, in Kalman and particle filtering.

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## THE WADSWORTH BCI RESEARCH AND DEVELOPMENT PROGRAM IN 2005

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The goal of the Wadsworth BCI Program is to develop non-muscular communication and control technology for people with severe motor disabilities and to establish this technology as a clinically practical and widely used method for improving their lives and the lives of their families and caregivers.

The program has focused on training people with and without disabilities to use sensorimotor (i.e., mu and beta) rhythms in the scalp-recorded EEG to control movement of a cursor on a computer screen. Recent work has substantially broadened this focus. Current efforts are concentrated on six objectives:

(1) To continue development and dissemination of BCI2000, the general-purpose BCI software system that can readily accommodate different signals, recording hardware, signal analysis and translation algorithms, and applications. The system has been provided free of charge to about 50 research labs throughout the world, and is being used in a wide variety of studies.

(2) To further improve EEG signal analysis and translation algorithms. We are developing user-specific methods for sensorimotor rhythm analysis. We are also exploring adaptive translation algorithms that select and continually adjust the recording locations and frequency bands used for control; and we are developing real-time non-hypothesis-driven methods for identifying and localizing useful brain signals.

(3) To further develop EEG-based multidimensional and sequential movement control. We are improving two-dimensional cursor control, and adding a select function, so that users can move a cursor (or a robotic arm) to a location and select (or grasp) the object located there. We are also developing a protocol for extending control to three dimensions.

(4) To develop applications using other EEG features, such as P300 and SSVEPs. Recent advances in P300 signal analysis and translation are substantially improving the speed and accuracy of matrix-based spelling.

(5) To explore BCI applications using electrocorticographic (ECoG) activity recorded from the cortical surface. Current studies are limited to people implanted with cortical surface arrays for short periods prior to epilepsy surgery. The higher amplitude, topographical resolution, frequency range, and signal-to-noise ratio of ECoG (compared to EEG) suggest that it may be extremely useful for BCI applications.

(6) To show that people with amyotrophic lateral sclerosis (ALS) and other severe motor disabilities can use BCI communication and control applications and that this use improves their lives. This work uses a simplified and easily portable BCI2000-based system and concentrates on studying people in their homes. It incorporates standardized methods for assessing quality of life.

In this work, we are collaborating with research groups in Tuebingen (led by A. Kuebler and N. Birbaumer), Atlanta (led by M.M. Moore), Tampa (led by E. Donchin), St. Louis (led by D.W. Moran), Seattle (led by J.G. Ojemann), and Rome (led by F. Cincotti).

**Acknowledgments**

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**Selected recent articles**

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# Abstracts of Posters and Demonstrations
(in alphabetical order)

# TOWARD IMPROVED SSVEP BCI SYSTEMS

Brendan Z. Allison[1], Dennis J. McFarland[2], Jonathan R. Wolpaw[2], Melody M. Moore[1], Gerwin Schalk[2], and Shi Dong Zheng[1]

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The GSU BrainLab has been collaborating with the Wadsworth Center on several projects involving SSVEP BCI systems. Our main goal was to show that SSVEP BCI systems could function without gaze shifting. Two major review articles (Kubler et al, 2001; Wolpaw et al, 2002), along with several SSVEP BCI papers (e. g., Gao et al, 2002, 2003), state that SSVEP BCIs depend on gaze shifting and thus would not work with users unable to reliably control gaze. Hence, there has been very little effort to develop SSVEP BCIs for severely disabled subjects. We have shown that SSVEP BCI systems can function without gaze shifting, and thus may have been overlooked as a viable communication system for patients. We plan to record from locked-in subjects over the summer to characterize performance with our new system. Our study also confirmed that sites O1 and O2 are the best sites for BCI control, consistent with most but not all other SSVEP BCI papers (e. g., Beverina et al, 2003).

In a related study, we sought to determine how consistent people's SSVEP activity is across several sessions. This is a vital issue in determining the optimal parameters for control. Results showed considerable inter-subject variability. Hence, some subjects could use the same site, frequency, and other parameters for SSVEP BCI control across multiple sessions and attain good performance. Other subjects would need a more sophisticated adaptive mechanism to determine the best parameters for each session.

We have conducted several other pilot studies aimed at characterizing SSVEP control. We have studied optimal stimulation frequencies, different displays including 2D SSVEP BCI, and different applications such as the right justified box (RJB) task often used with mu BCIs (eg, McFarland et al, 2003). One subject was able to attain 96% accuracy in a six choice task. This corresponds to about 15 bits per minute, an excellent result for an untrained subject. We are continuing to explore these issues and others, such as spatial filters, improved classification methods, effects of training, relevance of background and lifestyle factors, performance in noisy environments including subjects' homes, and novel applications such as a speller and control of external devices.

Funding provided NIH (NIBIB/NINDS)

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**SIGNAL REPRESENTATIONS BASED ON SINGULAR-VALUE DECOMPOSITIONS FOR DISCRIMINATION OF EEG FOR DIFFERENT MENTAL TASKS**

Chuck Anderson, Michael Kirby, James Knight, Tim O'Connor, Artem Sokolov
Colorado State University

Generalized singular-value decomposition is used to separate multi-channel EEG into components that optimize several different measures. These components may be used to filter out artifacts and to classify EEG according to which mental task is being performed. Examples are shown of the filtering of various artifacts, including some generated by an ALS patient's support systems. Examples of discrimination of EEG across a set of mental tasks are also shown.

Acknowledgment: National Science Foundation, Grant Number 0208958

**A NEW DESIGN OF THE ASYNCHRONOUS BRAIN COMPUTER INTERFACE USING THE KNOWLEDGE OF THE PATH OF FEATURES**

A. Bashashati, S.G. Mason, R.K. Ward, G.E. Birch
UBC/Neil Squire Society

The low-frequency asynchronous switch design (LF-ASD) was introduced as a direct brain computer interface (BCI) technology for asynchronous control applications. The LF-ASD recognizes scalp potentials related to Movement Related Potentials (MRPs) in the EEG signal. It has the advantage that it is operational at any time and not only at specific defined periods. It is activated only when a user intends control (IC state). Otherwise, it maintains an inactive state output (NC state) when a user is not meaning to control the device (i.e., the user may be idle, thinking about a problem, or performing some other action). The intended control (IC state) results from a certain movement attempt such as finger flexion. In the current design of the LF-ASD, the output state of the system at each time instant is determined by the values of the feature vectors at that specific time only. This paper presents the evaluation of a modified LF-ASD design with EEG data collected from individuals with high-level spinal cord injuries and able-bodied subjects. The modifications are related to incorporating into the system more knowledge about the movement attempt. Specifically, we present a method that finds the shapes of the path (using learning vector quantization method) that the features move during specific movement attempts (IC state) as well as the shapes during the No Control (NC) states. These specific shapes (path templates) are used to identify MRP patterns in the ongoing EEG signal and to trigger the output of the BCI system. The error characteristics of this new asynchronous brain switch design are significantly better than the previous LF-ASD design. The average true positive (TP) rates reaches 73% at false positive (FP) rate of 2% which is approximately 8.5% higher than the performance of the previous system.

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# CLASSIFICATION OF P300 WITH SVMS

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The P300 component of the ERP (Event-Related Potential) elicited by a visual or an auditory stimulus is usually considered as the most significant cognitive response of the individual to this stimulus. Therefore, many BCI research teams have focused their work on paradigms using this component of the ERP. In these P300-based BCIs, the brain waves are processed in real-time in order to detect when a so-called "target" stimulus has been perceived by the individual. Unfortunately, the P300 ERP can be very different among individuals, in space (electrode position) and time. Therefore, the parameters used by the system must be learned for each individual in order to discriminate optimally between the "target" and "non-target" stimuli.

Detecting P300 type ERP requires signal processing and data classification. In this work, we present a data classification technique based on support vector machines (SVM). We have used the spell-checking paradigm initially described by Donchin et al. The EEG signals are first filtered and decimated in order to remove as much noise and artifacts as possible. Then, the most significant space-time features of the waves are determined by several SVMs using different kernels: first, second and fifth order polynomials, and Gaussian.

The correct classification rates obtained on several datasets has been used as indices to determine the best decimation rate and the best kernel type for each individual. The generalization and consistency of this method have also been evaluated. On the one hand, we have tested the intra-session generalization, i.e. the fact that any word of a session can be used to learn the parameters of the classifier. On the other hand, we have analyzed the inter-session consistency, i.e. the fact that the parameters learned using one session can be successfully used to classify the responses in another session.

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## NESSI: A BCI APPLICATION

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University of Tübingen, Computer Engineering Department and Institute of Medical Psychology

The NEural Signal Surfing Interface (Nessi) is an extension of the web browser Mozilla. It enables BCI users to select links on a web site and to fill in forms with a built-in virtual keyboard, making e-mail and chat applications possible. Choices are presented in binary tree form, thereby allowing quicker navigation than many other accessibility products using linear 'Tab' navigation only. Mistakes can be corrected by backtracking along the decision tree. In principle, Nessi can be used in conjunction with any switch interface.

Nessi has interfaces to the BCI2000 and TTD software. It is currently being used by an ALS patient for web browsing and communication with relatives by internet chat. Nessi is available under the GPL and interested research groups are encouraged to use and extend the code.

# DO BCI SYSTEMS REALLY EXIST?

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In agreement with commonly used definitions, a BCI system can be divided into two main functional blocks:

1) The Transducer (TR), formed by the acquisition stage, the Feature Extractor and the Feature Translator. It is characterized by the biological signals used, the way they are acquired and processed, the classifier and by its output, described by a Logical Alphabet that in general has no semantic meaning;

2) the Control Interface (CI), that transforms (encodes) symbols of the logical alphabet or sequences of them into semantic symbols of a different alphabet (Semantic Alphabet), which can be used to drive external devices and consequently to interact with the environment. Examples of CI are encoders in a virtual keyboard application of the alphabets of natural languages (the English one, composed by 26 symbols or the Italian one, formed by 21 symbols).

Given a Logical Alphabet, the same TR can be used to drive different devices (which accept a compatible alphabet as input), such as a virtual keyboard on a PC screen or a wheelchair motor driver, as well as the same CI can be used in combination with different TRs. This means that in the BCI scenery it is very common (and easy) to mix and match TRs and CIs, thus providing a high level of customization. This suggests two main considerations:

1) There are two main areas in the BCI panorama: the first one whose goal is to optimize the TRs performances while the second one the translation of the logical symbols into semantic ones. Furthermore, the former is specific to BCI, while the latter is strongly related to information theory and is not directly correlated to brain signals. An additional area can be considered the one that addresses the problem of optimizing the tuning of CIs and TRs;

2) on the basis of the target application a CI could be better than another depending, for example, whether one wants to obtain the highest communication rate (e.g. a virtual keyboard task) or the lowest error rate (e.g. a wheelchair motor driver). The same observations can be applied to TRs.

By using some of the “BF++ Toys” (available at http://www.luigibianchi.com/bci.htm) one can simulate the behavior of a target application given a TR and a CI. It can be easily shown that different systems, composed by the same TR and by different CIs, provide in general different performances.

In this sense, the question “Do BCI Systems really exist?” is almost equivalent to the following one: “In a virtual keyboard application, are two BCI systems different just because one is implemented for the Italian language and the other one for the English one? ” If so, then two BCI systems are different for some reason that nothing has to do with brain signals. Otherwise, we have just realized that, dealing with BCI, only transducers exist (control interfaces belong to another world), a fact that would have “positive effects” on the way the performances of the systems could be evaluated ...

Acknowledgment: University of Rome"Tor Vergata"

# CORTICAL NEURAL PROSTHESES INSERTION: REMOVING THE MYSTERY

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Insertion of cortical neural prostheses elicits biological reactive responses that impair the long-term ability of these devices to record or stimulate neuronal activity. Reactive responses are the result of damage to the neurovasculature and neural parenchyma. We have developed several techniques that provide clear and accurate descriptions of the brain's vasculature. We are using these methods to investigate the role of the neurovasculature in the immediate and sustained responses to device insertion. By filling the vasculature using fluorescent resin we can generate casts at time points ranging from a few minutes to 6 weeks following insertion. Vascular casts revealed impaired perfusion around the insertion site following insertion that persisted for at least 24 hours. After one week normal perfusion was restored, and casts revealed the organization of neovasculature around the inserted device. Using fluorescent stains to label nuclei and neuronal Nissl substance, we examined the organization of the neurovascular unit normally and in response to device insertion. By filling the vasculature with physiological saline containing fluorescent dextran and microbeads instead of resin, we prepared live, labeled coronal slices that could be secured in a culture dish using fibrin glue. Real-time imaging of devices inserted into labeled slices was used to compare tissue deformation and vascular damage between different device tip shapes and insertion speeds. Video images revealed several kinds of vascular damage, including displacement of luminal contents, breakage, rupture, and vessel dragging. Damage to transcerebral arteries at times occurred over 100 μm from the insertion site, suggesting that initial damage to the neurovasculature may help determine the extent of reactive responses. Surprisingly, cortical surface features were one of the most influential factors affecting insertion damage; attempts to insert devices through pial blood vessels resulted in severe compression. Algorithms for automated image analysis were developed to track up to 100 interest points within each tissue sample during a single insertion. These measures permitted calculations of tissue deformation and maximum and effective strains achieved during insertion. Tip shape and insertion speed appeared to have independent effects. Three distinct deformation patterns have been identified based primarily on insertion rate. The results of these studies are being used to design the next generation of neural prosthetic devices and provide new insights for establishing safe insertion conditions.

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# THE BERLIN BRAIN-COMPUTER INTERFACE: RESULTS OF A FEEDBACK STUDY

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The 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 competences in control paradigms and a machine learning approach to extract subject-specific discriminability patterns from high-dimensional features. Thus the long subject training is replaced by a short calibration measurement (20 minutes) and machine training (1 minute). We report results from a study with six subjects who had no or little experience with BCI feedback. The experiment encompassed three kinds of feedback that were all controlled by voluntary brain signals, independent from peripheral nervous system activity and without resorting to evoked potentials. Two of the feedback protocols were asynchronous and one was synchronous (i.e., commands can only be emitted synchronously with an external pace). The information transfer rate in the best session was above 35 bits per minute (bpm) for 3 subjects, above 24 and 15 bpm for further two subjects, while one subject could achieve no BCI control. Compared to other BCI systems which need longer subject training to achieve comparable results we believe that the key to success in the BBCI system is its flexibility due to complex features and its adaptivity which respects the enormous inter-subject variability.

# DETECTION OF SENSORY EVENTS FROM ACUTE SPINAL CORD

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Neil Squire Society and University of British Columbia

Spinal cord injury (SCI) often causes permanent sensory and motor deficits. One avenue of research for partial restoration of function is neural prostheses. We suggest the spinal cord as a possible site for a sensory neural prosthesis. The main objective of this study was to investigate the feasibility of recording spinal cord neural activity in order to detect and classify external sensory information. Acute multi-channel extracellular recordings were used to extract neural spike activity associated with peripheral sensory information from the spinal cords of rats. Five classes of sensory events were recorded – electrical stimulation of the dermis in the four digits of rat forepaws comprised four classes of Sensory Events; another class consisted of periods during which no stimulation occurred (Idle Events). A simple feature extraction and dual-stage classification scheme using Principal Component Analysis and k-Means clustering was devised to classify external sensory events during single trials. The five classes of sensory events were correctly identified at a mean total accuracy of over 93%. Additionally, the discrimination of stimuli from periods of no stimulation was correctly identified at an accuracy of nearly 100%. Thus, we have shown the feasibility to detect and classify peripheral sensory information from multi-channel recordings of the spinal cord. This application may be useful following SCI in humans, for example, in a closed-loop neural prosthesis for restoration of hand grasp using functional electrical stimulation.

## DOES PHASE INFORMATION CONTRIBUTE TO CLASSIFICATION ACCURACY?

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Up to now, almost all brain-computer interfaces have ignored the relationship between the different electrode recordings by using e.g. bandpower or univariate adaptive autoregressive (AAR) parameters as feature vectors. However, there is evidence that there might be additional information in the relationship between single channels that can be explored by suitable features that incorporate these properties.

ECoG signals have already been explored offline (Brunner,2005) using the so-called phase-locking value (PLV) (Lachaux,1999), which represents the level of synchronization between two specific electrode locations:

$$PLV = 1/N\left|\sum_{n\equiv 1}^{N}\exp(j\left\{\phi_1(n)-\phi_2(n)\right\})\right|$$

Here, i(n) is the instantaneous phase of electrode i = {1, 2}. The average can be calculated over different trials or, for single-trial analysis, over several time samples. A PLV value of 1 means that the two channels are highly synchronized within the averaging window (this windows corresponds to N samples), whereas

a value of 0 implies no phase synchronization at all. Offline analyses were conducted by e.g. (Gysels,2004) and also at our lab, which demonstrated that there is additional information in the PLV as opposed to classical univariate features mentioned above.

Recently, an online model of the PLV was implemented and included in the Graz BCI system. A study is currently in progress, aimed at finding out if it is possible to control the classifier output when using phase synchronization features alone. To this end, we are using four monopolar EEG channels over C3, Cz, C4, and Fz. The PLV values are calculated within broad frequency ranges (8–30 Hz) and computed for 4 different electrode pairs (Fz-C3, Fz-C4, C3-Cz, Cz-C4). Preliminary results show that controlling the cursor on the screen is possible with 3 classes (left hand, right hand, and foot motor imagery). For example, a subject was able to reach an accuracy of > 75, during this online 3 class experiment after two sessions (a random classification would yield an accuracy of 33.33).

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**SIGFRIED AND ITS APPLICATION TO BRAIN-COMPUTER INTERFACES (BCIS)**

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Brain-computer interfaces (BCIs) enable users to use brain signals to control different output devices (Wolpaw et al., 2002). All current BCI techniques are hypothesis-driven and require extensive offline analyses that identify among all possible signals the brain signal features that the user can best control. Because this procedure has to be performed for every user and might be difficult if there are many possible signals, this procedure impedes the translation of current laboratory demonstrations into clinical applications.

We here present SIGFRIED (SIGnal modelling for Identification and Event Detection) as a novel method that removes the need for these lengthy signal identification procedures. This is accomplished by generating a description of the brain signal activity associated with rest by deriving a spatial-temporal Gaussian mixture model for each of the brain signal channels. Once this description has been obtained, BCI2000 software (Schalk et al., 2002) then calculates, for each point in time and each signal channel a score that indicates the similarity of current brain signal activity to the previously obtained resting activity. A topography of these scores can be visualized in real time, which allows for rapid identification of those channels that change with particular types of imagery. Using this new method, the user may control a BCI system without the lengthy and possibly difficult signal identification procedures that all current methods require. This method thus facilitates the transition of BCI systems from their current state of primarily laboratory demonstrations into clinical applications.

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**ONLINE LEARNING FOR THE IDIAP BRAIN-COMPUTER INTERFACE**

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For a Brain-Computer Interface (BCI) to be a truly effective tool that is useful to the user rather than frustrating, the BCI must have the ability to adapt dynamically throughout its use. The EEG signals received by the BCI will always change over time, both within a single session and between sessions, due to a number of factors: unintentional factors such as fatigue, intentional change in strategy by the user, and external factors such as signal noise and change in electrode position. So while at the beginning of each session the classifier will be initialised with respect to previous sessions, it must adapt itself to the particular signals it is receiving in the current session. However, this adaptation must be undertaken with great care – rapid changes in the classifier will confuse the user, and inappropriate adaptation will be catastrophic for the classifier. We are investigating methods of incorporating on-line learning into the IDIAP BCI, which takes the EEG signal from a 32 or 64 electrode cap and classifies the signal with a statistical Gaussian classifier. This system has been proven effective at differentiating between two or three mental states at a time (for example, imagination of left and right hand movement and a language-based task). This has been applied to problems such as operating simple computer games, and navigating a miniature robot around a model indoor environment with rooms and corridors. Work so far has involved the specific problem of the training phase, where the subject is told which command to give and so the real target is always known, making it a supervised learning task. We have been investigating various gradient-descent based learning algorithms that can be applied to the Gaussian classifier in an on-line manner. One such method is stochastic meta-descent (Schraudolph, 1999), which accelerates training by using local learning rate adaptation. Applying on-line learning to a BCI introduces another issue, however – since we are giving feedback to the user while training the classifier, there will be a mutual learning process as the user tries to adapt to the classifier while the classifier is trying to adapt to the user. To facilitate this process we would like the classifier to be changing in a reasonably stable and predictable manner to allow the user to adapt as the classifier changes. Imposing a smoothness constraint on the algorithms has produced good experimental results on artificial data, and initial results on real BCI data are promising.

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## THE UTILITY OF HIGH GAMMA BAND (80-250 HZ) ACTIVITY IN THE HUMAN SUBDURAL ELECTROCORTICOGRAM FOR BCI COMMUNICATION AND CONTROL

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The lab of Robert T. Knight at the University of California, Berkeley, uses scalp electroencephalography (EEG), subdural electrocorticography (ECoG), and functional magnetic resonance imaging (fMRI) to investigate the neurophysiology of attention, language, and prefrontal regulation of cognition, emotion, and action. The lab is now moving into BCI research as well. Most BCI studies focus on either 1) invasive multi-unit recording of action potentials from cortical neurons in non-human primates and rats, or 2) noninvasive recording of human EEG. The task-related high frequency power modulation seen in the human subdural electrocorticogram (ECoG), however, suggests that this high gamma band (80-250 Hz) ECoG signal may prove useful for BCI communication and control. Such high-frequency power modulation is unavailable to scalp EEG or conventionally-recorded spike-based BCI systems. In addition, since high gamma band power modulation is spatially constrained and well-predicted by sensory, motor, or cognitive task demands, the need for extensive user training may be substantially reduced. Our primary BCI research objective is to investigate the utility of the ECoG high gamma band for real-time BCI communication and control.

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# ASPICE - ASSISTIVE SYSTEM FOR PATIENT'S INCREASE OF COMMUNICATION, AMBIENT CONTROL AND MOBILITY IN ABSENCE OF MUSCULAR EFFORT

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The ASPICE project is aimed at the development of a technological aid which allows neuromotor disabled persons to improve or recover their mobility (directly or by emulation) and communication within the surrounding environment; this aim will be particularly addressed towards those stages of the disease in which the residual muscular strength could be not adequate, if present, for the utilization of conventional aids and in those conditions in which practical obstacles or security concerns could prevent a displacement from bed.

The key elements of the system are: - interfaces for easy access to computer, up to utilization of signals collected directly but non-invasively from Central Nervous System (Brain-Computer Interface, BCI); - controllers of intelligent motion devices which can follow complex paths, based on a small set of commands (Robotics); - information transmission and domotics, establishing an information flow between patient and controlled appliances, minimizing structural modifications of the house (Ambient Intelligence, AmI).

The output will be a communication-control integrated system, customized on the severely motor impaired patient's residual abilities, based on the aforementioned technologies. Clinical validation of the device and patients' feedback will be crucial for producing documentation and guidelines for customized system installation.

The design of the system has greatly benefited from the interaction with caregivers (especially at the UILDM – Lazio unit) and with the patients themselves (26 patients – and families – have so far expressed their interest in the project and their suggestions are currently being incorporated in the system design).

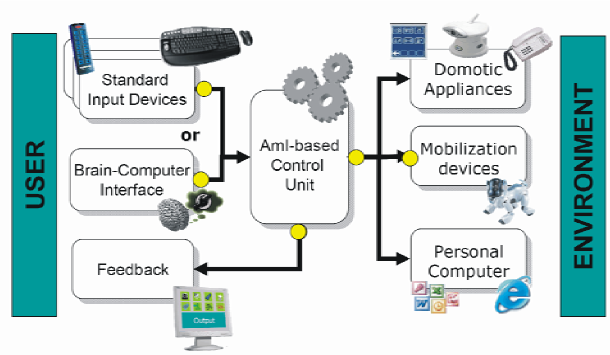

Figure 1

Keywords: Motor impairment; Assistive technologies; Environmental control Clinical science

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# DEVELOPMENT OF TEST PROTOCOLS FOR BRAIN-COMPUTER INTERFACING (BCI) TO INVESTIGATE MECHANISMS OF LANGUAGE DISORDERS

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Background

Neurological language disorders, e.g. resulting from head injury or stroke, may render a person unable to communicate effectively. If BCI technology could be used to investigate the mechanism of impairment, this would aid diagnosis and enable assessment of a person's ability to access BCI for communication and treatment purposes. A pilot study of normal subjects is in progress to develop protocols and signal processing techniques for a prototype BCI system.

Overall Aim

To establish a repertoire of appropriate sensory and cognitive EEG tasks for use in people with moderate language impairments, both for assessment and to generate EEG signals for operating a BCI system.

Specific Aims

To establish feasibility and produce normal baseline data, the aims are to:

1 Conduct pilot tests of event related potential (ERP) paradigms
2. Record continuous EEG during computer-based neuro-linguistic tests
3. Repeat protocols from previous studies of imagery tasks
4. Apply appropriate signal processing techniques to each test paradigm

Test Protocols

Multi-channel EEG (using international 10:20 system) to record responses to ERP based stimuli and cognitive tasks.

A. ERP recording using auditory paradigms:
a. deviant stimuli in an auditory oddball task elicit the P300
b. semantic incongruence e.g. words that do not fit in context at the end of a sentence elicit the N400, an EEG component associated with understanding language
c.Imagined auditory oddball task (under development)

B. Neurolinguistic Tests:
Continuous EEG is recorded during computer-based clinical language tests, being developed to enable objective assessment and correlation analysis with neurophysiological tests.

C. Cognitive Tasks:
a. Motor tasks: imagery of opening and closing a hand.
b. Non-motor tasks: auditory imagery of a favourite tune and spatial navigation imagery around a familiar environment.

Signal Processing Approaches

Novel signal processing techniques for BCI are being examined based around using Blind Source Separation (BSS) techniques, such as Independent Component Analysis (ICA). In particular, prior knowledge of the BCI paradigm (e.g. presence of P300, N400, etc.) will be used in semi-blind source separation to constrain the solution, extracting just the ERP of interest or verifying the presence/ absence of rhythmic EEG activity of interest to spatio-temporal and rhythmic based constraints.

**TREATMENT OF PROLONGED BRAIN MOTOR PLANNING TIME AND ELEVATED COGNITIVE EFFORT FOLLOWING STROKE: A PILOT STUDY**

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Purpose. The study purpose was to investigate 1) cognitive planning time; and 2) level of cognitive effort during a motor task in those with coordination impairment after stroke.
Background. Little is known regarding the relationship between cognitive processing and motor learning following stroke. Understanding this relationship in patients following stroke may assist in more accurately targeting motor learning interventions.
Subjects. In study 1, ten subjects with persistent (>12mo) arm dyscoordination (Fugl-Meyer upper limb motor score <34) and eight, age-matched healthy controls were compared.
Methods. Subjects performed a 14-cm, linear, shoulder/elbow movement (horizontal plane) that demanded pathway and target accuracy. Simultaneous, trigger-synchronized data were obtained for electroencephalography (EEG); electromyography (EMG; anterior deltoid and triceps); and kinematics of movement onset. Regions of cortical interest were ipsi-lesional motor and frontal areas. Onset of motor planning was defined as onset time of EEG-derived movement-related cortical potential (MRCP). Duration of cognitive planning was: time from MRCP onset to EMG onset at movement initiation(ms). Amplitude of cognitive effort was the amplitude of MRCP(μV). Group comparisons and pre-/post-treatment comparisons were made using a general linear model.
Results. Results showed that prior to treatment, stroke exhibited prolonged cognitive planning time vs controls in motor (2,734±1,205ms, stroke vs. 1,466±779ms, controls; p=.031) and frontal (2,596±1,082ms, stroke vs. 1,511±559ms, controls; p=.043) regions. Stroke had elevated amplitude of MRCP vs controls in motor (8.0±2.1μV, stroke vs. 4.9±1.8μV, controls; p=.009) and frontal regions (9.8±2.4 μV, stroke vs. 5.7±1.1μV, controls; p=.011). In study 2, a sub-sample of three subjects who had a stroke was treated 5hrs/day, 5days/wk, 12 wks using upper limb motor learning (re-tested, wk12). There was significant post-treatment improvement for cognitive motor planning time (p=.050) and level of cognitive effort p=.050) in the motor region.
Conclusions. Results showed that this sample with persistent dyscoordination had prolonged cognitive planning time and elevated cognitive effort, and that treatment may improve cognitive planning time and level of cognitive effort.
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# DEVELOPMENT OF A USER CUSTOMIZED ASYNCHRONOUS BRAIN COMPUTER INTERFACE BY MEANS OF GENETIC ALGORITHMS

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UBC, Neil Squire Society

An asynchronous Brain Computer Interface (BCI) continuously monitors the brain signal and is activated only when a user intends control. An asynchronous BCI system called the Low Frequency Asynchronous Switch Design (the LF-ASD) was designed by our group in the Neil Squire Society. It recognizes scalp potentials related to Movement Related Potentials (MRPs) in the EEG signals recorded from six EEG channels. After amplification, all the EEG channels are normalized with an Energy Normalization Transform (ENT). Then a low-pass-filter is used to decrease the interference with the features in the high-frequency band. A wavelet-like function is then applied as feature generator. PCA and 1-NN are then applied respectively for the reduction of feature space and feature classification.

Initial results from evaluation of the LF-ASD have shown promise, but the reported error rates are still high for many practical applications. Another problem associated with the LF-ASD is the number of design parameters that should be tuned for each subject. For each channel, five parameters should be selected (four for the feature extractor and one for the normalization), resulting in the total of 30 parameters for six EEG channels. Tuning all of these parameters manually is a cumbersome task, if not impossible. It should be also noted that since the shape of MRPs varies from subject to subject, this tuning should be done for each subject separately.

To improve the performance of the LF-ASD, we propose user customization using Genetic Algorithms. A GA will automatically tune the design parameters of the LF-ASD for a particular subject based on a given fitness function (the true positive rate for a fixed false positive rate). This results in an automatically customized asynchronous BCI for each subject.

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**MODULATION OF CORTICAL ACTIVITY BY MOVEMENT-RELATED PARAMETERS DURING IMAGINARY ISOMETRIC PLANTAR-FLEXIONS**

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Rehabilitation techniques may improve considerably if movement-related parameters can be differentiated by cortical potentials obtained during imaginary motor tasks, especially for implementation of EEG-based brain-computer interfaces (BCI) and neural prostheses. A multitude of studies have demonstrated a clear activation of the motor cortex during imagination of various motor tasks, however, it is still unclear if movement-related parameters (movement direction, range of motion, speed, force level and rate of force development) specifically modulates cortical activation as it does during the execution of actual motor tasks. Accordingly, this study examined whether rate of torque development (RTD) and/or torque amplitude modulates cortical potentials generated during imaginary motor tasks. Fifteen subjects imagined four different left sided isometric plantar-flexion tasks, while EEG and EMG recordings were performed. The averaged EEG activity was analyzed in terms of movement-related potentials (MRP), consisting of readiness potential (RP), motor potential (MP) and movement-monitoring potential (MMP). It was demonstrated that indeed RTD and torque amplitude modulate cortical activity during imaginary motor tasks. Information concerning movement-related parameters for imaginary plantar-flexion tasks seems to be encoded in the supplementary motor area (SMA) and the primary motor cortex (M1). A comparison between MRPs of imaginary and actual motor tasks revealed that early MRPs were morphologically similar, but they differed significantly in amplitude. One of the possible suggestions to explain such a difference may bean "abortion" of ongoing motor programs.

Acknowledgments: Vale do Paraiba University, Aalborg University

# BRAIN-COMPUTER INTERFACE RESEARCH AT THE UNIVERSITY OF WISCONSIN - MADISON

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Brain-computer interface (BCI) technology has the potential to provide patients with severe motor disabilities greater independence and a higher-quality life. BCIs take recorded brain signals and translate them into real-time actions, in this case movement of a cursor on a computer screen. Patients with temporary subdural electrode implants are subjects for evaluating the feasibility of using electrocorticogram (ECoG) signals to control a BCI. Training methods, mental effort and workload will be significant factors in the success of BCIs as a means of communication and independence for individuals who rely upon them. This research will contribute to the understanding of human subject training and learning when using a BCI.

Four patients with a clinical need for intracranial ECoG monitoring underwent temporary subdural electrode grid implantation at the University of Wisconsin or William S. Middleton VA Hospital. Subjects were trained over multiple sessions to control a computer cursor with their brain signals. Subjects first go through several screening sets where they imagine movements or sounds when they see a cue on the computer screen. This data is analyzed offline to find signal features that can potentially be modulated by the subject, and small segments of the chosen frequency band(s) are assigned to certain directions of cursor movement. Subjects then use their brain signals to control the vertical movement of a cursor moving across a computer screen at a set rate towards a target. In a 2-target task, the size of each target is the vertical height of the screen and they appear one at a time in a random order. Each testing set is composed of 10-20 trials and during each trial autoregressive algorithms determine the cursor movement in real time. BCI2000 software is used for all experiments.[1] Accuracy, improvement on the task over time and response to perturbations are methods of evaluating performance. Subjects also fill out questionnaires before and after each session as a measure of subjective mental effort.

Subjects modulated their ECoG signals well enough to perform at 70% accuracy on a 2-target task by the second testing session (total time < 45 minutes). With multiple sessions, subjects performed at 100% for a 2-target task and two subjects were able to perform at levels of accuracy at least twice that of chance for 3 to 8-target tasks. Two subjects with electrodes over temporal and parietal cortex attained cursor control at an accuracy of up to 100% for 2 to 8-target tasks, despite the location away from motor areas. This finding indicates that brain areas not previously considered ideal for BCI control can be used and could prove to be superior to motor areas.

1.Schalk, G., McFarland, D.J., Hinterberger, T., Birbaumer, N., Wolpaw, J.R., BCI2000: a general-purpose brain-computer interface (BCI) system. IEEE Transactions on Biomedical Engineering, 2004. 51(6): 1034-43.

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## AUTOMATIC DETECTION OF INTERACTION ERRORS FROM EEG

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IDIAP Research Institute

Brain-computer interfaces (BCI), as any other interaction modality based on physiological signals and body channels (e.g., muscular activity, speech and gestures), are prone to errors in the recognition of subject's intent. An elegant approach to improve the accuracy of BCIs consists in a verification procedure directly based on the presence of error-related potentials (ErrP) in the EEG recorded right after the occurrence of an error. Most of these studies show the presence of ErrP in typical choice reaction tasks where subjects respond to a stimulus and ErrP arise following errors due to the subject's incorrect motor action. However, in the context of a BCI, the central question is: "Are ErrP also elicited when the error is made by the interface during the recognition of the subject's intent?" In other words, let's imagine that the subject's intent is to make a robot reach a target to the left. What would happen if the interface fails to recognize the intended command and the robot starts turning in the wrong direction? Are ErrP still present even though the subject did not make any error but only perceived that the interface is performing wrongly? We have thus explored whether ErrP also follow a feedback indicating incorrect responses of the interface and no longer errors of the subject himself. Four healthy volunteer subjects participated in a simple human-robot interaction experiment (i.e., bringing the robot to either the left or right side of a room), which seem to reveal a new kind of ErrP. This "Interaction ErrP" exhibits a first sharp negative peak followed by a broader positive peak and a second negative peak (~270, ~400 and ~550 ms after the feedback, respectively). But in order to exploit this Interaction ErrP we need to detect it in each single trial using a short window following the feedback that shows the response of the classifier embedded in the BCI. We have achieved an average recognition rate of correct and erroneous single trials of 86.4% and 77.5%, respectively. These figures have been obtained using a 10-fold cross-validation where testing is always done on a different recording session to those used for training the classifier. We also show that the integration of this Interaction ErrP in a BCI, where the subject's intent is not executed if an ErrP is detected, yields significant improvements in the bit-rate of the BCI.

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## BRAIN COMPUTER INTERFACE AT AALBORG UNIVERSITY

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A new modularized on-line system has been developed interfacing to Neuroscans NU-amp system. The system retrieves the continuous EEG signals from the amplifier, buffers a window of N samples and then pass it trough a pipe, where several modules (feature extraction, feature translation and application) process it. Different windows, length of windows and window overlapping may be applied to each channel, giving different time and frequency resolution for each of them. The modules are replaceable allowing the user to switch among different feature extraction, feature translation and applications, thus, different BCI systems may be implemented using this software. Currently the research carried out with this program is focused on frequency analysis of single trials of steady-state visual evoked potentials (SS-VEP). A computer screen presents the subject with a matrix of 3 by 3 squares, each flickering at different frequency and labelled with a number from 1 to 9. The spectrum of the EEG signal elicited on the Oz electrode when the user focuses his attention on a specific number shows its biggest peak on the stimulation frequency, its second harmonic or its third harmonic, what gives us a unique spectrum for each of the nine flickering frequencies. This feature of the SS-VEP allows the computer to detect the transmitted number by detecting the frequency of the visual stimulation. Three modules are use by this system: FIR filter, FFT and feature translation using amplitude criteria. A fourth module is being developed, which will translate the numbers chosen by the subject into text. This will be done by using the T9 PredictiveText Input. Softwarefor that has been implemented in collaboration with at the Intelligent Multimedia Department of the Aalborg University. We are currently working on implementing that into our BCI system.This BCI based on SS-VEP appears to be a promising approach since accuracy of up to 92.8 % can be achieved with symbol signaling rate of 12 chars per minute. Besides, the required training time seems to be negligible and high detection speeds are possible, even though some control of eye movements is still needed. The current efforts on this kind of BCI are directed towards the implementation of the "multi-tap" alphabet in connection with predictive text input in order to speed up the information transfer rate and promote an efficient communication tool for patients.

Funding support acknowledgment: Aalborg University

**EXPLORING BRAIN FUNCTIONS BY USING BCI AND SIMULTANEOUS EEG/FMRI TECHNIQUES**

Girolamo Garreffa, Luigi Bianchi, Seung Schik Yoo, Walid Kyriakos, Maria Grazia Marciani, Bruno Maraviglia
Enrico Fermi Center, University of Rome Tor Vergata, Harvard Medical School

The simultaneous use of EEG and fMRI can provide a powerful tool for investigating spontaneous and evoked brain activity, due to the complementary advantages of the two techniques in terms of temporal and spatial resolution. However, the combination of these techniques results in the occurrence of specific artifacts that affects the EEG signals. Our aim is to carry out technical and methodological solutions in order to make possible EEG/fMRI brain function investigation during BCI tasks.
The first source of noise is due to the pulse MRI sequence artifact (PSA), induced by magnetic gradient switching during MRI scan. However, even if its amplitude can be of tens of millivolts, it can be easily removed due to its stereotyped nature so that it does not represent a problem in the vast majority of cases.

The second source of noise is the ballistocardiogram artifact (BCA), a large signal simultaneously visible on all EEG traces and determined by cardiac activity inside magnetic field. Actually it represents the main problem as it is not stereotyped and it is of large amplitude (up to a hundred of microvolts). It is important to know if it can be removed in real-time and which is the best method to do that. Some EEG based BCI sessions (without feedback) were performed into the scanner (without the presence of gradients) in order to see if and how it was possible to detect reproducible EEG changes (spectral changes) during the execution of different mental tasks in order to have a reference measure unaffected by MR artifacts.

Preliminary results suggests that during mental tasks there are chances to make the system work even in the presence of the BCA, provided that the execution of each task is long enough (as it seems to be with 15 seconds of trial duration). On the other hand, BCA suppression (by means of ICA or other subtraction techniques) can improve the ability of the classifiers and dramatically reduce the time required to perform a classification and the duration of a trial.

These considerations are relative to spectral data analysis based on FFT, which is the classical way to analyze quantitative EEG data. However, BCIs can use different spectral estimators in order to reduce the delay in which the feedback is provided to the user: FFT is usually performed on 1 sec length EEG segments while other methods work well with just hundreds of ms time series. It should be noted that 200ms of BCA free signal are available in the EEG trace, while 1 second of EEG will contain almost for sure at least 1 heart pulse. However, even in this "worst FFT based case", preliminary results suggest that the system will work.

We conclude that the use of EEG to drive a human-machine feedback, while collecting fMRI, should be possible and represents a very interesting approach for BCI methods and provides a new perspective in the study of brain functions.

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# PERFORMANCE EFFECTS OF ICA AND SPATIAL PCA PREPROCESSING SCHEMES OVER SVM-BASED CLASSIFICATION OF P300 EVENTS

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The present work was motivated when considering new processing requirements for Data Set II (P300 speller paradigm) presented for the BCI Competition III [1]. This data shows real signal issues such as contamination with several artifacts. We tried two different techniques in order to automatically remove the artifacts and also to reduce information dimension. We compare three methods in regard to individual electrode classification efficiency [2]

a) Band pass filtered direct EEG. Band pass filtered direct EEG.
b) ICA based restoration of EEG with automatic component selection.
c) Spatial PCA estimation in signal subspace for generation of virtual EEG leads.

In all cases, temporal samples were used as features for classification.

# AN ASSESSMENT OF ECOG SIGNALS FOR DIRECT BRAIN COMMUNICATION

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Electroencephalography (EEG) is the most often used recording method for brain-computer communication, and although it is non-invasive and thus readily available, it has a number of disadvantages. These include poor signal-to-noise ratio, reduced spatial resolution, and susceptibility to artifacts, which are limiting factors for the performance of brain-computer interfaces. An alternative method is the electrocorticogram (ECoG), which has been used by far fewer research groups, primarily because it requires the implantation of subdural electrodes. The close proximity of the ECoG electrodes to the cortical surface alleviates some of the limitations of the EEG. Recent advances in signal processing have provided new powerful techniques that can considerably improve the signal-to-noise ratio of multivariate signals. Considering that, one might argue that employing these methods may make EEG signals less inferior compared to ECoG signals rendering invasive methods like ECoG recordings unnecessary for BCIs. However, this is not the case. Our results show that by using state-of-the-art spatial filters which linearly integrate information over multiple spatially distributed sensors, the classification performance in EEG recordings can be significantly increased so that it is almost in the range of the results achieved for unpreprocessed ECoG recordings. Applying the same preprocessing to ECoG data, however, further improves classification as well and yields very high classification rates. Considering the fact that the locations of the ECoG electrodes were based solely on clinical considerations for epilepsy monitoring and therefore did not consistently cover brain areas that are known to be most suitable to record brain patterns associated with motor activity, it can be assumed that the differences between EEG and ECoG recordings are even more signifcant. Our results clearly demonstrate the potential of ECoG as a promising recording method for direct brain-computer communication.

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**BCI-INFO.ORG: AN INTERNATIONAL PLATFORM FOR BRAIN-COMPUTER INTERFACE RESEARCH**

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The past few years have seen an increased interest in BCI research resulting in a large number of new research groups. BCI research is an interdisciplinary field integrating knowledge from neuroscience, psychology, engineering, computer science, and rehabilitation. Seldom does any single group have the expertise in all these fields required to develop and improve a workable BCI. Therefore, it is important to have forums in which results and issues common to BCI researchers from these diverse disciplines can be discussed. Unfortunately, these are usually limited to conferences and special workshops, the rarity of which often stifles the required discussion and exchange of information. Further, useful information about BCI research is scattered over scientific publications and websites maintained by individual research groups. In order to mitigate this situation, we suggest an internet platform for BCI research. It is intended to be a repository of everything related to BCI research, containing information for researchers and patients alike (e.g. ALS patients). The site will also contain instructional materials written for a lay audience, so that students, media, and others from the general public can find current, accurate, and easy-to-read information about BCIs. A prototype of the suggested platform based on the open source content management system Plone is already available at http://www.bci-info.org. Plone provides a powerful and flexible system that is easy to use and maintain. BCI-info.org is currently organized to provide moderated and unmoderated content. In order to ensure a certain quality of the information, BCI-info.org also maintains a workflow for reviewing content to be published in the moderated section after being accepted by the review board. BCI info.org currently provides a discussion forum and several content types including bibliography, software, research groups, scientific journals, and events. Incorporation of the BCI framework suggested by Steve Mason at al. [1] to improve the content organization is currently under consideration. Everyone is encouraged to contribute and help to build and improve BCI info.org so that it can serve the BCI community as a useful platform.

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# MOBILE BRAIN-COMPUTER INTERFACE ON THE POCKET PC

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A brain-computer interface is normally based on a biosignal amplifier, a data acquisition device and a PC or notebook for the signal processing. Such a system configuration can be used e.g. for the realization of a language supporting system where the patient can select letters or words on the display of the notebook. But for assistive applications like a TV channel selection or a wheelchair mounted language supporting program, an embedded system including the amplifier, data acquisition device and the processor without mechanical disks is more suitable. Size, robustness, ease, and convenience of use are major considerations for assistive communication devices. The hardware must be fully portable, supplied by a battery and cheap [1].

The mobile brain-computer interface uses a standard IPAQ Pocket PC from HP as portable host and is connected via a serial cable to an embedded target computer system g.MOBIlab (see Figure 1). The embedded system consists of a μC operating at only 12 MHz to optimize the power consumption. A 16 Bit analog to digital converter samples 8 analog channels with 256 Hz each. The module is equipped with 4 EEG channels, 2 ECG channels and 2 analog inputs for external sensors. Two digital inputs and 2 digital outputs allow to control external devices. Four AA batteries power the embedded system for 180 hours. The Pocket PC operating system is Pocket PC 2003 and the BCI system was programmed in Embedded Visual C++. The integrated Wireless LAN (WLAN) module of the Pocket PC can be used for wireless data transmission. Data are stored on the internal 64 MByte storage or streamed to a Compact Flash card for later analysis. The Pocket PC is performing the parameter extraction, classification and visualization of the experimental paradigm.

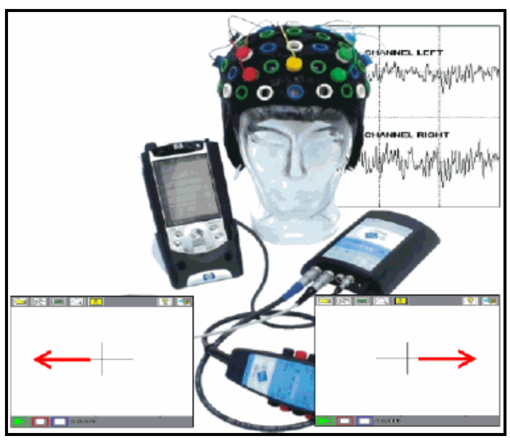


Figure 1: Components of the mobile brain-computer interface. The arrows are indicating if a right hand or left hand movement should be imagined.

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# LOCAL FIELD POTENTIAL SPECTRAL TUNING IN MOTOR CORTEX DURING REACHING AND DRAWING MOVEMENTS

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In this study, local field potentials (LFPs) were recorded from the motor cortices of monkeys (Macaca fascicularis) while they preformed a standard 3D center out reaching task and a 3D circle drawing task. During the center out task, the subjects held their hands at the location of a central target and then reached to one of eight peripheral targets forming the corners of a virtual cube. For the circle drawing task, a circular track appeared at the either the center or one of the corners of the virtual cube used in the center out task. The subjects had to trace three consecutive circles in either the clockwise or counter-clockwise direction. The spectral amplitudes of the recorded LFPs were calculated, with the high frequency LFP (hf-LFP) defined as the average spectral amplitude change from baseline from 60 to 200 Hz.

A 3D linear regression across the 8 center out targets revealed that 6 % of the beta LFPs (18-26 Hz) and 21 % of the hf-LFPs were tuned for velocity ($p$-value $< 0.05$), while none of the beta or hf-LFPs were tuned for position. The tuned hf-LFPs were used to train a linear model relating the hf-LFPs to hand velocity during the center out reaching movements to the eight targets. The model was then used to predict the hand velocity during the circle drawing task. The predicted circle drawing velocity profile was highly correlated with the actual hand velocity profile with an average correlation coefficient of 0.91 at an average lag of 133 ms.

These results suggest that continuous control of a multi degree-of-freedom brain-machine interface is possible using high frequency LFP recordings in motor cortex.

Acknowledgements: The Whitaker Foundation

## COMPARATIVE EVALUATION OF INDEPENDENT COMPONENTS ANALYSIS ALGORITHMS FOR ISOLATING TARGET-RELEVANT INFORMATION IN BRAIN-SIGNAL CLASSIFICATION

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We present results from two binary BCI experiments. The first is an motor imagery experiment with 5 subjects (classification based on frequency features of the signal---essentially mu activity) and the second is a paradigm based on covert shifts of attention to auditory stimuli with 15 subjects (classification based on averaged segments of the time series---essentially ERPs). We have previously reported good classification performance using Support Vector Machines in both cases (Lal et al 2004, Hill et al 2005). In addition, Recursive Channel Elimination (Lal et al 2004) has been reported to be an effective feature-selection tool for reducing the number of necessary features on both data sets, and in the motor-imagery experiment it reliably identifies the channels near the motor cortex as most important.

Here we demonstrate that, prior to classification, blind source-separation using Independent Components Analysis (ICA) consistently improves classification accuracy by roughly 10%. In addition, after recursive elimination of the Independent Components by a method analogous to that of Lal et al, the number of features required for classification is considerably smaller. For the motor imagery experiment, we compare a number of different variants of ICA, reporting that error rates and feature reduction in InfoMax ICA (see Makeig et al, 1996) are significantly better than the other variants for most subjects. Across different random subsets of the signal, we also examined the stability of the algorithms, in terms of variation in the spatial weighting of electrodes in the components ranked as most important by recursive elimination. InfoMax ICA proved to be markedly the most stable of the variants tested, particularly for the best-performing subjects, reliably weighting the channels near the motor cortex most highly and in a consistent pattern.

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**ACTIVITY OF MOTOR CORTEX CELLS AND MUSCLES DOCUMENTED IN FREELY BEHAVING PRIMATES WITH AN IMPLANTED BRAIN-COMPUTER INTERFACE**

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Studies of motor cortex function traditionally involve recording neural activity during repetitive trained tasks within a restricted workspace (e.g. cued reaching to prescribed targets). This approach offers both technical and methodological advantages, since stable recordings can be obtained most easily under head-fixed conditions, and reducing the dimensionality of movements aids the interpretation of modulated cortical activity. However, extensive training may affect neural representations of particular tasks, and a limited movement repertoire yields a correspondingly restricted set of data. In contrast, neurally driven prosthetics intended to restore a full spectrum of motor function would need to extract movement-related information from cortical neurons during completely unrestrained activity. To this end, we have developed an implanted brain-computer interface (or 'neurochip') and used it to record neuronal and muscular activity in two monkeys during extended periods of free behavior, and during a trained wrist-tracking task. The neurochip sampled signals from one of 12 electrodes chronically implanted in primary motor cortex, and EMGs from up to four arm muscles. Unit action potentials were identified and onboard computation of spike rate and mean rectified EMG over 100ms bins allowed long continuous recordings to be stored in memory. Data from 12-hour periods of unrestrained behavior (including free movement and feeding in a cage, and natural sleep) were used to cross-correlate cortical spike rate and EMG. During waking behavior positive correlation peaks were observed with some contralateral muscles (r: 0.05 - 0.3) within +/-0.2 s of zero time-lag, but not with ipsilateral muscles ($r < 0.02$). In many cases, peaks were well fitted by the sum of a wide Gaussian component (FWHM: 6 - 25 s) and a narrower component (FWHM: 0.7 - 2.6 s). These peaks may reflect, respectively, periods of generally elevated activity during behavioral episodes and the activation of specific synergies within each episode. Correlation coefficients were generally lower during performance of the trained task than during unrestrained behavior. Some neurons exhibited a cross-correlation peak with unrestrained wrist muscle activity despite showing no task-related modulation, suggesting that single-joint movements may involve only a subset of all arm-related neurons. These results reveal that during natural behavior motor cortex and muscle activity are correlated over several time scales, and extend previous observations made under restrained conditions. They also confirm the ability to record movement-related activity from cortical cells over prolonged periods of free behavior, an important requirement for neural prosthetics to restore motor function.

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# BRAIN COMPUTER INTERFACING (BCI) RESEARCH PROGRAMME, UNIVERSITY OF SOUTHAMPTON

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This relatively new Research Programme unites biomedical engineering and the clinical sciences, based within the Life Sciences Interfacing and Neuroscience initiatives at the University of Southampton, providing a cohesive scientific basis for rehabilitation research and management. Clinical problem driven projects take cutting-edge signal processing research, producing an investigative tool for advancing knowledge of neurophysiological mechanisms, whilst providing a practical therapeutic system for use outside a specialised BCI laboratory.

The overall aim is to help bridge the gap between major advances in signal processing and the relatively limited success in practical applications of BCI. This emerging Programme includes disciplines in: neuromuscular physiology, biomedical signal processing, computational intelligence, medicine, physiotherapy, Speech & Language Therapy, psychology and computer science. Further national and international collaborations are being explored to enhance achievement of the Programme's goals.

Programme Themes:
1. Advancing BCI for scientific investigation and diagnosis
2. Through BCI, elucidating neurophysiological mechanisms of normal function, dysfunction and recovery, guiding research into therapeutic interventions
3. Development and applications of signal processing techniques:
· Continued development of Blind Source Separation based signal processing techniques.
· Minimal EEG channels for practical implementation through dynamical systems.
· EEG denoising techniques tracking brain activity through semi-blind source separation.
· Comparative studies of different paradigms for specific applications allow assessment and development of techniques suited to different BCI paradigms.
4. Characteristics of person-friendly systems to widen accessibility and compliance:
· ease of user tasks (not too skill-dependent)
· minimal training periods
· broad range of task options available for individual choice

**UCLA NEUROENGINEERING PROGRAM AND BCI RESEARCH**

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Neuroengineering is a new, exciting, challenging, and multidisciplinary field of research. The goal of the UCLA NeuroEngineering Training (NET) Program is to prepare graduate students to be leaders in the revolutionary technological developments that will affect neuroscience in the 21st Century. By expanding the synergies between the UCLA Brain Research Institute (BRI) and the Henry Samueli School of Engineering and Applied Sciences (HSSEAS), the objectives of the NET Program are (1) to enable students with a background in biological science to develop and execute projects that make use of state-of-the-art technology; (2) to enable students with a background in engineering to develop and execute projects that address problems that have a neuroscientific basis, and (3) to instill in all trainees the capacity for the multidisciplinary teamwork that will be necessary for new scientific insights and dramatic technological progress. This effort brings together departments from the life and medical sciences (e.g., neuroscience, neurology, neurosurgery, neurobiology, psychology, etc.) and the physical sciences and engineering (e.g., biomedical engineering, chemical engineering, computer science, electrical engineering, material science, mechanical engineering, applied mathematics, physics, etc.). This poster will describe the neuroengineering research that the trainees in our program at UCLA are pursuing. Examples include: microprobes for Parkinson’s disease research, microelectrode arrays for high-density neural stimulation and retinal prostheses, simulating the synthetic vision provided by retinal prostheses, micromachined systems to manipulate individual cells and to perform high-impedance patch-clamp recording, wireless neural transceivers, and neural control systems for spinal cord injury, ocular motility, and deep-brain stimulation.

# HOW KNOWLEDGE OF THE EXACT TIMING OF FINGER MOVEMENTS AFFECT CLASSIFICATION IN BCI

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Many online BCI systems are based on classification of finger movements (Wolpaw et al., 2002). In some of these systems the detection of the start of the movement is essential for good classification accuracy. The goal of this study was to examine the effect of this uncertainty on the classification results.For this purpose data gathered during online BCI sessions were further analyzed offline.

Four right-handed subjects (one female, 20-25 years old) participated in a online BCI study. The goal was to move a cursor left or right towards a target object.During the experiment a short flash of light was presented every two seconds and subjects were asked to perform brisk index finger movements immediately after observing the light. Exact timing of movements were measured with light port detectors. The experiment consisted of a "fake" online session and two real online sessions.

During the fake session, a cursor moved always towards the target and the gathered data was used to construct a preliminary classifier for the upcoming online session. Classifier for the second online session was trained with data from the first online session. Each session contained approximately 300 finger movements. Classification was performed with early-stopped committee of 10 multi layer perceptron networks using temporal features. Features were computed from low frequency (1-7 Hz) components of potentials related to the beginning of movement.

In the online sessions features were computed from a predefined time window after the cue light without any knowledge of the exact timing of the finger movement. In the offline analysis the time window was positioned according the light port sensors. The classification results were compared. Clear negative correlation between variance of the reaction times and classification performance was observed.

Preliminary results show that classification using exact time information of the finger extensions resulted in 6 % increase in average performance. However, in real BCIs the exacts timing information is unavailable. Hence, the results show that it is important to develop methods for automatic detection of the start of the finger movements.

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## EEG GAMMA-BAND POWER AND TIME-DOMAIN FEATURES AS SEPARATE SINGLE-TRIAL BRAIN COMPUTER INTERFACE INPUTS

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Gamma-band activity (28-40Hz) is known to be associated with attention and voluntary motor tasks. In the present study gamma-band power and time-domain predictive features serve as two separate dimensions of input into a Brain Computer Interface (BCI) device. Time-domain features predict intent to initiate movement and gamma-band power features determine laterality of desired movement.

Subjects were presented with two types of auditory selective-attention tasks: one containing a target stimulus, appearing unilaterally; and the other containing two target stimuli, presented interchangeably to either ear. Target stimuli required motor response in the form of a button press with the ipsilateral index finger.

EEG was recorded using a 20 channel system with a chin reference (International 10-20 system). Data was sampled at 256Hz with cutoff frequencies at 0.1 and 100Hz. Off-line data was low-pass filtered at 48Hz.

Frequency-domain data analysis was based on spectral power of signals and estimated with the multitaper method. Average multitaper-estimated spectra of the data showed a significant difference in power in the gamma-band, between left and right movement tasks. No subject training was required in order to achieve this power spectra difference.

Time-domain analysis, based on averaged signal amplitude, showed a difference between movement and non-movement sections in 360ms prior to motor response. Thus information contained in the time course preceding actual motor response can be used as a predictive tool in a BCI device.

Single-trial classification, using Support Vector Machines, was performed in two separate dimensions. Classification between left and right movements was conducted using frequency-domain features; classification between movement and non-movement segments was done using time-domain features.
Features were chosen according to electrodes with the most significant difference ($p<0.001$) and concentrated at frontal and central electrodes. Single-trial classification using frequency-domain features resulted in 75.7% accuracy, averaged across four subjects. Classification using time-domain features resulted in 72.3% accuracy, averaged across four subjects.

Comparing the two types of auditory selective-attention tasks showed that gamma-band activity was maximized when subjects attended to a single target, as opposed to multi-target attention. In the multi-targeted movement task, difference between left and right averaged spectra was insignificant, resulting in single-trial left/right movement classification accuracy of only 50% across subjects. Hence, gamma-band activity is state-dependent (attended side) rather than response-dependent (movement side).

## AN EEG INVERSE SOLUTION BASED BRAIN-COMPUTER INTERFACE

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Typically, a brain-computer interface (BCI) system extracts, from scalp-recorded EEG, particular components or features encoding human intention and conveys the resulting control signals to the external world. One type of brain-computer interfaces is based on the detection and classification of the change of EEG rhythms during different motor imagery (MI) tasks, such as imagination of left- and right-hand movements. The spatial pattern of brain activity, when observing over the scalp surface, is blurred due to the effect of the head volume conductor, especially the low-conductivity skull. Applying source analysis methods, which solve the EEG inverse problem from noninvasively recorded scalp potentials, allows imaging brain signals in the source space. The reconstructed source distribution or representation over certain cortical regions can be regarded as an alternative of intracranial recording. Thus it carries high-resolution spatial information on brain activity, which facilitates detecting motor imagination.

We have investigated in our lab the use of EEG inverse solutions, or source analysis approaches, to facilitate noninvasive EEG applications. Before inverse calculation, preprocessing steps - Laplacian spatial filtering, band-pass filtering, noise normalization, SVD denoising and independent component analysis (ICA), are used to isolate MI-task-related signals from background noise and baseline activity. Based on different source model, single- or two-dipole fitting procedures, or distributed current density estimation can be performed to evaluate which side of brain (either left or right) presents dominant activity. Our working hypothesis is during motor imagery, due to a decrease in synchrony of the underlying neuronal populations, a decrease of power appears in the μ rhythm of the contralateral side of the brain (i.e. if the subject is imagining to move his/her left hand, the power decrease appears on the right side of the brain). Since we used noise-normalized data for source analysis, such decrease of power on the contralateral side of the scalp turned to the phenomenon of showing stronger activity on the ipsilateral side. Therefore, the equivalent dipoles or cortical current density corresponding to the noise-normalized data shall appear or be stronger on the ipsilateral side of the brain. We have tested our source analysis based algorithms using a public dataset and the results are promising, suggesting that these newly developed algorithms may provide useful alternative for noninvasive BCI application.

**MOVEMENT-RELATED POTENTIALS AND SENSORIMOTOR CORTICAL RHYTHMIC ACTIVITY OF TETRAPLEGICS**

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There are only a few reports on how persons who really would benefit from BCIs use them. Here our aim was to examine motor-cortex activity of tetraplegics and how it reacts to attempted movements.

Subjects were four right-handed male tetraplegics. Level of injury was C4-C5 and time since injury from four months to five years. Three of the Patients (S1-S3) were classified as ASIA A and one of them (S4)h as ASIA B. Four right-handed males acted as controls. Recordings were made simultaneously with a 306-ch MEG and 60-ch EEG. One of four visual stimuli (duration 0.5 s, ISI 3 s) instructed patients to attempt to lift the left, the right, both index fingers, or not to attempt any movements. Controls performed real movements. All subjects were instructed to perform or try to perform prompt movements after the stimulus disappeared. Two 16-minute sessions with 80 repetitions of each task were recorded.

Slightly contralaterally dominant movement-related potentials (MRPs) were recorded with EEG in all patients. Due to technical problems, evoked magnetic fields could be measured with MEG only from one subject. The phasic MRPs were much slower than in the controls. Especially the premovement potentials were contralaterality dominant. 10- and 20-Hz activity was detected in the sensorimotor cortex with both MEG and EEG. This activity reacted to the movement attempts bilaterally. The suppression of the 20-Hz activity was not followed by the strong rebound, as in healthy subjects. Especially with MEG the suppression of the mu-rhythm seems to be more widely distributed than in healthy subjects.

Acknowledgment: Graduate School of Electronics, Telecommunications and Automation

# MAXIMUM SIGNAL FRACTION ANALYSIS FOR ARTIFACT REMOVAL IN EEG

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Signal Fraction Analysis is a subspace method for performing signal separation. The subspaces necessary for signal separation can often be defined by less data that the higher order statistics used by methods such as ICA. We show how the generalized singular value decomposition can be used to separate linearly mixed
signals under some assumptions. We also compare this approach to other methods commonly used in the BCI literature.

# TRAINING BRAIN-MACHINE INTERFACE SYSTEMS BY CONTROLLED PLASTICITY

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We developed a research paradigm for studying mechanisms of neural plasticity within a brain-machine interface (BMI) system that consists of the brainstem of a lamprey interconnected with an external device. This setup provides for a bi-directional exchange of information between the neural preparation and the external system.

Our studies investigated an increase in the neural output after tetanic stimulation. The neural preparation controlled the orientation of a simulated robot. Each trial started from a random initial orientation of the robot. At each moment, the orientation of the robot was represented by the neural input rate, spanning the range between 0 and 3 Hz. The neural output - the instantaneous spike rate - was used as a "steering wheel" of the robot, i.e., it defined the rate of change of the robot orientation.

The desired behavior for the BMI system was to steer the robot into a fixed target orientation. At each moment, a computer generated a target output signal such that, if it were controlling the robot, it would smoothly steer it into the target orientation. The target output was used as a reference signal. If the neural output deviated too far below the target output, a tetanic burst was triggered.

To assess changes in neural activity, we analyzed changes in both the neural output signal and in the trajectories of the external system. We observed significant changes in both short- and long-term scales. To measure the behavioral changes, we computed an average squared deviation of the robot orientation from the target. It decreased significantly in the long-term scale as a result of applying of the tetanic stimulations.

These findings suggest that it is possible to control the behavior of bi-directional BMIs by the induction of long-term plastic changes.

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## ONLINE ADAPTATION FOR BCI

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We study the problem of non-stationarity in the operation of a BCI. The Berlin BCI aims to adapt to the user, and learn from data recorded during training sessions. This data is used to train classifiers that map between EEG data and 2-3 classes used as control signals.

However, these classifiers often perform differently in online settings, due to changes in the subject's brain processes. Such changes may be a result of fatigue, or the change in attentional focus while performing tasks, or the increased visual stimulation in online scenarios.

We propose several adaptive schemes to counter this problem and study their performance on data recorded during online experiments. We also explore the possible neurophysiological causes of nonstationarity, and present evidence supporting these hypotheses. A surprising result of our study is that, in combination with our powerful feature selection scheme, simple adaptive methods can significantly increase performance of the classifiers.

**MEASURING THE PERFORMANCE OF BRAIN-COMPUTER INTERFACES USING THE INFORMATION-TRANSFER RATE**

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A number of performance measures have been used in the BCI community, such as hit rate, character rate, accuracy, information-transfer rate. Some of these measures are clearly interdependent; for instance, the classifier accuracy decreases when the number of tasks increases or when the protocol speed increases. The information-transfer rate (ITR) is used as a performance measure because of its objective nature. Nevertheless, despite being objective, the ITR is not well suited for all BCI protocols and applications; this is in particular the case for asynchronous BCIs and for pointing devices. In fact, the best performance measure is application dependant. The existing ITR definitions are reviewed in the poster and their limitations discussed.

As the ITR depends on the accuracy, protocol speed and number of tasks, and as these measures are interdependent, an optimal protocol speed and number of tasks must exist. A noisy channel carrying information models the BCI, with the ITR as a performance measure. The features are modeled with a Pulse-Amplitude Modulated signal and are classified using a Bayes classifier. As a particular case, it will be shown how average-trial protocols (e.g. based on the measurements of P300 evoked potentials) can be modeled in order to determine the optimal protocol speed. This approach also permits to derive the corresponding optimal number of mental tasks. More generally, such modeling also shows that the accuracies of classifiers currently used in the BCI community are not high enough to permit significant improvement on the ITR.

This study emphasizes the fact that more effort should be made on the protocols to improve on the speed, as well as on features selection and classifier design to improve on the accuracy. Nevertheless, when evaluating several state-of-the-art classifiers, no significant enhancement could be observed in terms of accuracy. It appears that more significant improvements could be obtained at the level of the communication protocol, as well as by simultaneously using (if feasible) other modalities. These conclusions should be discussed with other researchers and a poster is an excellent opportunity to do so.

This work is supported in part by the Swiss National Center of Competence in Research (IM)2, Interactive Multimodal Information Management (http://www.im2.ch/), as well as by the European Network of Excellence SIMILAR (http://www.similar.cc).

**P300 MATRIX SPELLER CLASSIFICATION**
**VIA STEP-WISE LINEAR DISCRIMINANT ANALYSIS**

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Farwell & Donchin (Electroencephalogr Clin Neurophysiol, 1988) describe a BCI that operates by determining the stimuli that elicit a P300 event-related potential. The subject is presented with a 6x6 matrix containing alphanumeric characters and symbols. The columns and rows of the matrix intensify at random, in a serial sequence, and the user's task is to count the number of times a particular character flashes. The row and column containing the attended character elicit a P300, while the other 10 rows and columns do not. The attended character can be identified by detecting the row and column that elicited a P300. For the P300 data competition associated with the meeting, a wide variety of preprocessing techniques were applied to enhance the P300 feature extraction, including: baseline correction, band-pass filtering, sub-sampling, spatial filtering, principle component analysis (PCA), and independent component analysis (ICA). In addition, a diverse set of classification techniques were implemented including: support vector machines (SVM), kernel methods, linear discriminant analysis, statistical based weighting, as well as boosting and bagging techniques. Interestingly, this sundry set of algorithms resulted in remarkably similar performance. This poster will show that a comparatively simple linear discrimination technique, step-wise linear discriminant analysis (SWLDA), with minimal preprocessing is both efficient and notably effective for classifying P300 matrix speller responses. Offline analysis from 5 subjects will be summarized, illustrating the effects of feature selection on the performance of the SWLDA method. To demonstrate the effectiveness of the SWLDA method online, classification performance from 4 subjects will be presented.

**BCI-BASED CONTROL OF VIRTUAL ENVIRONMENTS**

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In recent experiments in Graz virtual reality (VR) is used as feedback medium and thereby subjects are able to move through a virtual environment (VE), based on the BCI classification output [1,2]. Four healthy subjects participated in these experiments and the performances of three different feedback (FB) conditions are compared: (i) a bar FB on a PC, (ii) a head mounted display (HMD) as FB device and (iii) a highly immersive 4-wall projection environment, commonly referred as “Cave” for FB presentation.

Two mental strategies were used: either imagination of right hand vs. left hand (RL) or right hand vs. foot/leg (RF) movements. Therefore two different virtual environments have been used. For RL a nearly circular conference room was used with the HMD and a virtual bar in the Cave FB respectively. For RF two slight different models of a virtual street have been used.
In case of the virtual conference room or bar experiments the imagination of a right or left hand movement reacts in a rotation inside this VE to the right and left, respectively. If the virtual city was used as a feedback medium, a foot motor imagery resulted in a movement and a right hand movement resulted in stop of any motion. In case of the simple FB a horizontal bar moved on a monitor to the right and left or to the right and downwards, respectively, depending on the output of the LDA classifier. In all performed VR experiments only the relative class information of the LDA output was used and the absolute LDA value was disregarded. Additionally this feedback was summed up over the whole run.

All subjects were able to navigate in the different VEs and the achieved BCI performances in the VR tasks were comparable to standard BCI recordings with the horizontal bar. The usage of VR as FB was stimulating for the subjects performances. Especially in the Cave condition (highest immersion) the performance of 2 subjects was excellent (up to 100% BCI classification accuracy), although variability in the classification results between individual runs occurred. One reason for some inferior classification results of individual runs especially in the Cave condition (classification error of 32% in subject 1 and 18% in subject 2) could be the loss of concentration in connection with a moving visual scene.

The experiments demonstrated that “thought”-based control of VE is possible even when the user is placed inside high immersive environments. Whether a VR as feedback has an impact or can shorten the training time needs further investigation.

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**ONLINE CLASSIFICATION OF FINGER MOVEMENTS**

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Four right-handed subjects participated in an online BCI study. Subjects' task was to move, by means of finger-movement related EEG activity, a circle towards a target on the left or the right side of the feedback window. Subjects performed brisk left or right index finger extensions immediately after a LED flashed (ISI=2s). A trial ended when the ball hit the target (minimum 5 steps, 10 cm), went to the opposite side of the window or maximum number of steps for one trial (15) was reached.

Classification was based on slow movement related (0.5-7 Hz) potentials occurring 500 ms before and 500 ms after the LED onset measured from 5 bipolar channels (F3-F4, C3-C4, P3-P4, FC1-FC2 and CP1-CP2). The experiment consisted of a simulated online session and two real online sessions. EEG related to the finger movements was not classified in the simulated online session. However, the circle moved towards the target so that the subjects became familiar with the feedback. The classifier used in the first online session was taught on the basis of the signals in the simulated online session and the classifier used in the second online session was taught on the basis of the signals in the first online session.

The mean classification accuracies of movement related potentials in the second online session for the four subjects were 69.2%, 74.4%, 77.2%, 73.5%. Targets were reached in average of 16.6 s in 83.1% of the trials and in the rest the maximum number of steps was reached.

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**FORCING THE PACE FOR BRAIN COMPUTER INTERFACES (BCI): LRP AND /B- ERD EVOKED BY FAST FINGER-TAPPING.**

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Introduction: Brain-Computer-Interfaces (BCI) enable the control of external devices via EEG signals rather than the brain's normal output pathways. One key problem is the still limited information transfer. Increasing the rate of BCI-commands might be restricted eventually by the refractory behavior of EEG features such as event-related desynchronizations (ERD) of pericentral b rhythms or lateralised readiness potentials (LRP). On the other hand, combining these EEG-features might improve the detection and classification of motor intentions in BCI settings.

Objective: We report a study in healthy subjects addressing the stability of ERD and LRP for increasing rates of selfpaced typewriting and compared intraindividually averaged data with intraindividually single-trial classified data.

Methods: 8 healthy subjects performed selfpaced typewriting (randomised left vs right index finger tapping on a computer keyboard) in blocks with 30, 60 or 120 keystrokes per minute. Using 64-channel EEG recordings, we compared intraindividually LRP and /b-ERD parameters.

Results: Averaged data in 7 out of 8 subjects showed LRPs clearly lateralised to the corresponding (contralateral) primary motor cortex at all three tap rates. The same 7 subjects showed lower /b- power over the contralateral than the ipsilateral motor cortex at all three tap rates.
In the single-trial LRP-classification error-rates ranged from 5-35% in all three tap rates, and between 15-50% in the ERD data. Feature-combination (LRP and ERD-features) improved classifications in two/third of all results.

Conclusions: These findings demonstrate that two different motor-related EEG-features can be detected with physiologically plausible scalp topographies preceding finger movements performed at repetition rates as high as 120 taps per minute. Single trial analysis in BCI scenarios call for a deeper analysis of sequential effects, i.e., the role of rhythm rebounds will be subject of further studies.

# NEUROELECTRICAL SOURCE IMAGING OF MU RHYTHM CONTROL

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Neuroelectrical inverse problem solution allows estimation of cortical current densities from non invasively picked up scalp potentials. Such a signal provides a better insight on the cortical activity, since they show a much higher spatial resolution than scalp recordings and allow a direct match with anatomo-functional structures of the cortex. However, a verification of the usefulness of cortical estimates in the contest of a brain computer interface has not been performed yet.

Four well trained (80 < accuracy < 96%) subjects, underwent a series of recording while they were trained to gain control on a mu-rhythm BCI (BCI2000 recording software [1] with two targets RJB task). EEG was recorded by using a high resolution EEG cap with 59 channels. During the early phases of the training, the subjects had been asked to perform hands or feet movement imagination to move the cursor upward or downward, respectively.

A model of the subjects' head as volume conductor was generated from MR images. The estimation of cortical activity during the motor imagery task was performed in each subject by using the depth-weighted minimum norm algorithm [2] and spectral analysis of r2 values for each one of the about five thousand dipoles constituting the modelled cortical source space.

Five different scalp spatial filtering methods, e.g. Raw (ear referenced) potentials, CAR, Small, Large and Spherical Spline Laplacian, and one cortical source estimate were compared, according to the attitude of spatially conditioned EEG segments to predict the target (r2).

Sessions were either analyzed separately, or in pairs; the latter method aimed at testing the sensitivity of the spatial filters on different montages. R-square maxima over all features were marked for each session and were compared across conditioning methods, both in the "screening" and in the "generalization" modality.
Figure 1 shows the comparison of scalp distribution of r2 values at the most responsive frequency. Raw EEG data show the least r2 values, while Spline Laplacian and Source Imaging estimates show the highest values and most localized topographies.

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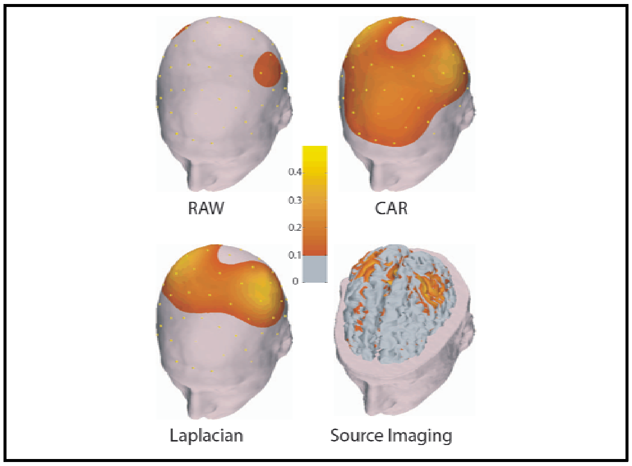

## THE WADSWORTH BCI RESEARCH AND DEVELOPMENT PROGRAM: DEMONSTRATIONS OF CURRENT WORK

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**Thursday Evening**

A person uses sensorimotor rhythms recorded over right and left sensorimotor cortices: (1) to control two-dimensional movement of a cursor to one of several targets; and (2) to then select or not select the target the cursor has reached. This sequential control emulates full mouse function and might be used to control reach and grasp by a robotic arm.

**Friday Evening**

A person uses P300 to spell words through the 6x6 Donchin matrix protocol. With the most recent signal analysis algorithm, the user can spell up to 1 letter/8 sec with nearly 100% accuracy. With word prediction, this capacity might achieve 4-5 words/min, and might go higher with a defined vocabulary.

This ongoing work is supported by grants from NIH (NICHD, NIBIB, NINDS) and the James S. McDonnell Foundation.

**IDENTIFYING AND USING ECOG SIGNALS FOR BCI CONTROL USING ACTUAL AND IMAGINED MOVEMENTS**

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Leuthardt and others demonstrated a working BCI using electrocorticography (ECoG). Actual and imagined motor tasks were used to identify signals the subject could control (i.e., screening procedure). This screening procedure is discussed across 10 individuals. Methods of furthering this screening are implemented and discussed. Edge effects within active and passive epochs of the same task are discussed, as well as the difference between real and imagined screening paradigms. The importance of adjustment after an initial session of control is demonstrated. Feature selection by correlation coefficients is the current method for feature selection; this method is compared with a support vector machine classification. The efficacy of different areas (tongue, hand, foot, and others) is discussed as well as results of actually controlling a cursor using each.

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# BIOMETRIC CONTROL WITH A GALVANIC SKIN RESPONSE INTERFACE

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Biometric input devices can provide a non-muscular channel for controlling assistive technology devices for people who have very severe motor disabilities. Brain-Computer interfaces are promising but sometimes do not work for people whose cortex has been affected by injury or disease. This study explores a biometric control interface based on the Galvanic Skin Response (GSR), to determine its controllability and effectiveness as a channel of input. This poster presents longitudinal data from one locked-in subject who could no longer use a BCI device, but was successful in using a GSR-based communication device. We also include a control study with twenty-one able-bodied subjects. We present issues with GSR control, and approaches that may improve accuracy and information transfer rate.

The study consisted of a simple guided selection task, asking the user to "please generate a yes" (to activate the GSR beyond a threshold) or "please generate a no" (keep the GSR levels below the threshold). The results from the locked-in subject showed a wide variance in controllability ranging from 30%-80% accuracy over time. We attribute the variance to intermittent subject fatigue and medications, and noticed a marked decline in performance after the first session of each day. However, the subject is currently using the GSR effectively as his primary means of communication and has been able to spell using a binary selection paradigm at a very slow rate (3 characters per 1.5-hour session.) Applying offline algorithms to the data has allowed us to increase the potential accuracy to close to 95%, and we are retrofitting the online system to utilize the most effective algorithms.

The able-bodied subjects were tested with one session in a highly distracting real-world environment (a science fair). With no training, the performance accuracy ranged from 60-100% accuracy on a simple guided selection task.

The results from this study demonstrate that the GSR can be used as a control interface and has provided us with many ideas for improving its performance. We are currently conducting this same series of GSR studies with three more people who have locked-in syndrome. Our goal is to more completely characterize GSR controllability and to determine optimal techniques for training, imagery, and user interfaces. We are also experimenting with real-time analysis algorithms that provide the best accuracy, and heuristics for tuning a GSR system for an individual's abilities. In addition, we are in the process of adapting our existing assistive technology applications [9] to accept GSR input, with the aim of significantly improving the quality of life for people with locked-in syndrome.

**OUTPUT EFFECTS EVOKED BY MICROSTIMULATION OF CERVICAL SPINAL CORD IN SEDATED MONKEYS -IMPLICATIONS FOR NEUROPROSTHETIC APPLICATIONS**

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Effects of stimulating lumbar spinal cord have been investigated in cat1, rat2 and frog3, but there is no somatotopic map of the output effects evoked by stimulating sites in primate cervical spinal cord. Such data would be important for neuroprosthetic applications involving hand and arm. We examined the forelimb movements and muscle responses (EMGs) evoked by intraspinal microstimulation in three M. Nemestrina monkeys (2 male, 1 female) sedated with ketamine. Electrode penetrations were made in regularly spaced tracks from C6 to T1 with stimulation delivered at 200 μm increments in each track. Trains of 3 stimulus pulses at 300 Hz were delivered once/sec at currents ranging from 10-90 μA to evoke movements. Hand or arm movements were evoked at 79% of the 764 sites stimulated. Specifically, movements were evoked in fingers (59% of effective sites), wrist (9% of sites), elbow (20%) and shoulder (12%). To determine the muscles activity evoked by a stimulus current just capable of eliciting joint rotation, stimulus-triggered averages of rectified EMG were calculated at each site where a movement was observed. Typically, many muscles were coactivated at threshold currents needed to evoke movements (figure). Out of an average of 15 muscles recorded per animal, only one muscle was active at 14% of the effective sites, two to three were simultaneously active at 23% of sites; four to six muscles were coactivated at 24% of sites, and more than six muscles were active at 39% of sites. For example, post-stimulus effects occurred in finger flexor muscles at 66% of sites from which movements were evoked, and finger extensors were activated at 50% of all sites. Finger flexor and extensor muscles were co-activated at 44% of all sites. Thus, intraspinal stimulation at currents adequate to evoke movement typically coactivated multiple muscles, including antagonists. Histologic reconstruction of stimulation sites indicated that responses were elicited from the dorsal and ventral horn and from fiber tracts in the white matter, with little systematic topographic organization for movement or muscle activation relative to anatomic features. These results suggest that placement of neuroprosthetic electrodes in the cervical spinal cord to elicit hand and arm movements will need to be guided primarily by output effects evoked by stimulation.
Acknowledgment: NS12542, RR00166

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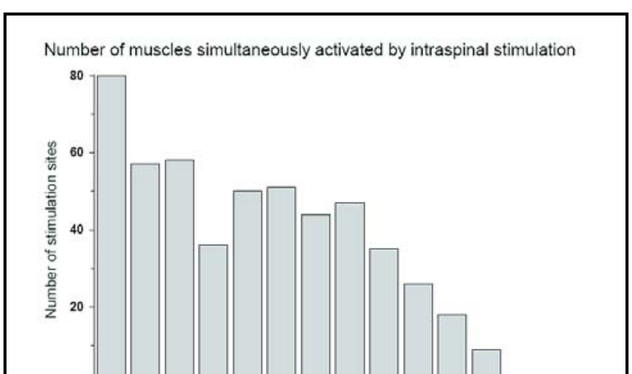

# SSVEP-BASED BRAIN-COMPUTER INTERFACE FOR COMMUNICATION AND CONTROL

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Brain-Computer Interfaces (BCI) can be based on different brain signals. One major group of BCIs uses oscillatory components of the ongoing electroencephalogram (EEG) which are mentally modified by the user. Another group of BCIs is based on steady-state visual evoked potentials (SSVEP). A flickering light source causes a SSVEP with the corresponding flickering frequency, measurable over the occipital cortex, when a user shifts his gaze to these stimuli. SSVEPs have the same fundamental frequency as the stimulation frequency, but often they also include higher and /or sub-harmonic frequencies.

In this work the influence of higher harmonics to the classification accuracy of a 4-class BCI system was investigated. Frequencies were set at 6, 7, 8 and 13 Hz so that the harmonics did not influence each other. A custom built stimulation unit was used to generate the flickering lights by the use of LED-bars. In a first study with nine subjects, cues were randomly presented indicating the flickering LED-bar which should be focused. This was repeated resulting in 80 trials (5 s each) each class.

Performing single trial analyses it was found that the more harmonics (up to three) were used as features, the merrier the classification result increased. These findings were used to set up an online operating BCI system.

Five subjects performed one training session and two sessions with feedback (720 trials total, 5-s trials). In these feedback experiments the users got a “cockpit” presented, displayed on a computer screen. A highlighted bar at the “horizon” indicated the LED-bar to focus. The subjects received performances (25 % equals random) between 42.5 % and 92.1 %. Shortening the trial length to 3 s, one subject received an average accuracy of 94.4 % (160 trials) equaling in 31.96 bit/min.

This feedback experiment was modified to serve as a virtual keyboard (VK) where letters can be selected through 3 steps. The alphabet is firstly split into two halves (16 letters each), then into 4 groups (4 letters each) and at least into 4 letters. Therefore the 4-class BCI works in the first step as 2-class, in the other 2 steps as 4-class BCI. In a series of copy spelling sequences (maximum of 100 trials per sequence, 4 s per trial) a subject increased the spelling rate from 1.65 to 4.26 letters/min.

This VK has some advantages compared to former presented ones [1,2]: (i) The first alphabet level is a 2-class problem, means that the probability for a correct selection is higher than in the other two levels. (ii) In both alphabet halves of the first level a “delete letter” is included. In the case of a wrong letter the user has only to correctly select the “delete letter” in level 2 and 3.

The work was supported by the Lorenz-Böhler Gesellschaft and “Allgemeine Unfallversicherungsanstalt -AUVA”.

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**IMAGERY OF MOTOR ACTIONS: EFFECTS OF KINESTHETIC VERSUS VISUAL-MOTOR MODE OF IMAGERY IN SINGLE-TRIAL EEG**

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Single-trial motor imagery classification is an integral part of a number of brain-computer interface (BCI) systems [1, 2]. For motor imagery tasks in BCI research, the subjects are usually instructed to imagine themselves performing a specific motor action without overt motor output. However, dependent on the exact manner of how subjects perform this task, the relative contribution of visual and kinesthetic representations may vary and, as a result, distinct processes may be involved. In the present study we investigated the EEG patterns sensitive to different types of motor imagery. In particular, the instruction how to imagine action was varied to create (i) kinesthetic motor imagery (MIK) as a first-person process and (ii) visual-motor imagery (MIV) as a third-person process. For control purposes also 'real conditions' were examined, i.e., motor execution (ME) and visual observation of physical hand movements (OOM), respectively. The goal was to identify relevant features of the ongoing multi-channel EEG (i.e. electrode locations and reactive frequency components) that represent the specific mental processes.

Based on multi-channel EEG recordings in 14 right-handed participants we applied a learning classifier, the distinction sensitive learning vector quantization (DSLVQ) to identify relevant features (i.e. frequency bands, electrode sites) for recognition of the respective mental states [3]. With the features computed from a reference and the features extracted from the task interval (e.g. imagery task) for all trials (separately for each task and for each electrode position) a DSLVQ classification was performed. This method uses a weighted distance function and adjusts the influence of different input features (e.g. frequency components) through supervised learning. The classification accuracies obtained for MIK were better than the results of MIV. Moreover, the focus of activity during kinesthetic imagery was found close to the sensorimotor hand area, whereas visual-motor imagery did not reveal a clear spatial pattern.

The results confirm previous studies that motor imagery can be used to 'produce'; (movement-)specific and locally restricted patterns of the oscillatory brain activity. However, good recognition rates were solely achieved when the 'imaginer' used the strategy of kinesthetic motor imagery (first-person process), whereas recognition was almost impossible when the participant formed a visual image of another's action (third-person process).

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## AN EEG BASED-BCI TO OPERATE A PROSTHETIC HAND AND OTHER DEVICES

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A Brain-Computer Interface (BCI) system was developed to operate a prosthetic hand and other devices. The EEG signals were recorded with one or two bipolar channels over the sensorimotor areas during left hand, right hand or foot motor imagery. Autoregressive modeling method was used to extract the features from the spontaneous EEG signals and Linear Discriminant Analysis (LDA) incorporated with statistical rejection criteria was used as the classifier. Three subjects participated in the asynchronous experiments. The optimal electrode locations and the two mental tasks used in the online experiments were identified from the EEG trials collected during the offline experiment by using the results obtained from the LDA 10x10 fold cross validation. The mental tasks of imaginary left hand and imaginary foot movements were selected for these three test subjects. The online classification errors for these subjects were between zero and 17.5% during the synchronous experiments. In the asynchronous experiments, the subjects were required to complete a preprogrammed test sequence consisting of selections of 4 different prosthetic hand movements and 4 LEDs representing 4 different devices, resets and two resting intervals. The optimal time to complete the test sequence that is computed by assuming the percentage of true positive and false positive are 100% and 0% respectively is 6 minutes and 20 seconds. The times taken for the subjects to complete the test sequence was found to be between 8 minutes 20 seconds and 17 minutes. In the test sequence, the unintended activations per minute generated by the subjects varied from zero to 0.8 per minute. The performance of a BCI system is normally measured in terms of classification accuracy and communication rate. For the present application of a BCI to control a prosthetic hand and other devices, a high classification accuracy with low errors (unintended activations) is more important than a high communication rate. By introducing thresholds in the classification rule and averaging the LDA outputs over 5 seconds to arrive at a decision, we minimize the false positives although in the process, the true positives and the communication rate were reduced. The results of the present study to use the BCI system to control a prosthetic hand and other devices show good promise. However, the system performance is sensitive to changes in the mental states of the subjects. There is a need to investigate what type of mental training will enable the subjects to control their brain signals in a way that will improve the performance of the BCI system.

**COMPARING SENSORIMOTOR RHYTHMS, SLOW CORTICAL POTENTIALS, AND P300 FOR BRAIN-COMPUTER INTERFACE (BCI) USE BY ALS PATIENTS - A WITHIN SUBJECTS DESIGN**

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Severely paralyzed people often need communication tools that do not depend on muscle control. Brain-computer interfaces (BCIs) measure specific features of brain activity and translate them into device commands. Most current noninvasive BCIs use sensorimotor rhythms (SMR), slow cortical potentials (SCPs), or the event-related P300 potential. We are comparing BCI use with these features in people with amyotrophic lateral sclerosis (ALS) in a within subject design. We are also assessing the interaction of psychological variables (i.e., current mood, motivation, quality of life, depression) and BCI use.

Using the BCI2000 system, 8 people have been trained or are being trained to use SMRs or SCPs to control cursor movement to targets on a computer screen. During SMR training, patients were presented with targets consisting of a red vertical bar that occupied the top or bottom half of the right edge of the screen and a cursor on the left edge. The cursor moved steadily across the screen, with its vertical movement controlled by SMR amplitude. The subject's task was to move the cursor to the height of the target so that it hit the target when it reached the right edge. With SCP training, patients had to move the cursor vertically either to the upper or lower half of the screen. The vertical movement of the cursor was achieved by increasing or decreasing the SCP voltage level by a criterion amount. Each patient completes 20 training sessions with each feature. In addition, 7 people have been trained for 10 sessions to use P300 to select items from a 6x6 matrix according to Donchin's paradigm (Farwell and Donchin, 1988). A copy spelling task consisting of a standardized sentence was given. The user makes a selection by counting how many times the row or column containing the desired letter flashes.

The 4 people who have completed SMR training all learned to control cursor movement with an accuracy of at least 75% (with 50% expected by chance). Of the 7 people who have completed P300 training, 4 were successful with accuracies in the last training session ranging from 62,7 % to 86,6 % (with 2,77 % expected by chance). After ongoing training two patients achieved accuracies up to 100 %. In contradiction, two patients started with high accuracies but performance declined over sessions. While a few people have mastered SCP control, this feature has proved less successful to date.

These initial results suggest that SMRs provide the best overall performance across users with ALS. SMR seems to be more reliable over time than P300. In addition, although P300 based BCI has an apparent advantage in that it requires no initial user training, it appears to be effective for some users only. SCP use seems to be more difficult and to require more training. Psychological variables appear to affect performance, e.g the motivational factor 'fear of incompetence' decreases over sessions. This suggests that their evaluation could help improve BCI training protocols and help to establish the practical value of BCI applications.

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**CLASSIFICATION OF ATTEMPTED FINGER LIFTS BY TETRAPLEGIC SUBJECTS FROM SIMULTANEOUS MEG/EEG RECORDINGS**

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We have conducted an off-line analysis with tetraplegic patients, an actual user group who would benefit from BCI applications. The goal was to classificate brain activity related to attempted left and right index finger lifts. With attempted finger lift we mean that the tetraplegic subjects try to actually lift the finger. It has been shown that with subjects with spinal-cord injury the motor cortical areas respond to motor attempts.

Analysis was done off-line from simultaneous MEG/EEG recordings. Data was recorded from three male tetraplegics, all classified as ASIA A with complete tetraplegia. Subjects were 31, 24 and 24 years old and have been injured for 5 years, 2 years and 4 months, correspondingly. Analysis was done on single trial basis. All measured trials were included to analysis and not rejected e.g. due to artefacts etc. Two types of features were extracted: The first set of features was based on Bereitschaftspotential (BP), which precedes voluntary initiation of movement. The second set of features was based on theta band activity, which corresponds to episodic memory process responsible for orientation in space and time.

The features were classified using two approaches: batch trained classifier and dynamic classifier. In batch training a classifier is trained using a set of previously collected samples and remains constant afterwards. But the non-stationary nature of the brain activity alters the feature space over time, rendering the classifier less effective. The dynamic classification enables the classifier to follow changes in the feature space caused by the non-stationarity.

For the dynamic classification particle filter (PF) was used. Particle filters are sequential Monte Carlo algorithms for solving on-line Bayesian inference problems. Particle filter was used to sequentially update the parameters of the classifier function.

With batch trained classifiers the classification accuracies with BP features were slightly higher when the features were calculated from MEG. For theta band features the classification accuracy was significantly higher for features derived from MEG. Using BP features, left and right finger movements could be differentiated with average classification accuracy over subjects of 83% and 81% for MEG and EEG, correspondingly. For theta band features, corresponding classification accuracies were 78% and 65%.

The use of dynamic classification increased the classification accuracy for all subjects and for both feature types. The improvement was 2-4 percentage points for features from MEG recordings and 3-6 percentage points for EEG features. The improvement was statistically significant for EEG features of two subjects.

Acknowledgment: Academy of Finland

# THE GRAZ BCI: A DEMONSTRATION

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Graz-BCI:
With one laptop we will show a presentation of the Graz-BCI system. Different slides explaining our system and movies showing the application of the Graz-BCI will run in an endless loop. The applications to be presented are:
Control of a virtual keyboard with motor imagery and SSVEP
Control of neuroprosthesis with surface electrodes or implanted electrodes
Navigation through virtual reality
BCI-controlled table tennis

BIOSIG - software demonstration:
The second laptop will be used for software demonstrations.
BIOSIG is an open source software library for biomedical signal processing and available from http://biosig.sf.net. It supports over 30 different data formats, includes functions for quality control, artifact processing, feature extraction and classification as well as viewing and scoring software. Moreover, some standard methods for analyzing BCI data are included. The demonstration will present the BIOSIG toolbox and its use in BCI research.

The rtsBCI library, licensed under the GNU Public License (GPL), provides modules for real-time data acquisition, storage, signal processing and visualization based on Matlab, Simulink, the Real-Time Workshop and Microsoft Windows operating system.

BCI-info.org - An International Platform for Brain-Computer Interface Research:
An internet platform for BCI research is intended to be a repository of everything relating to BCI research, containing information for researchers and patients alike (e.g. ALS patients) interested in BCI research. Although the content currently available is limitted, this will hopefully improve soon. Everyone is encouraged to contribute and help build and improve BCI info.org so that it can serve the BCI community as a useful platform.

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**BIOPRINTING FOR MULTISITE, MICRODRUG DELIVERY WITH IMPLANTABLE MICROELECTRODE ARRAYS AND SELECTIVE CELLULAR BINDING ON PLANAR MEA'S**

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Current microelectrode technology successfully allows for short-term recordings of extracellular neuronal signals. However, over the long-term, the immune response to these implanted electrodes tends to electrically isolate the implant from the neural tissue, potentially causing them to fail. Thus for consistent long-term recording, it may be necessary to control the immune response so that the electrical/neural tissue interface remains intact. One method to do this would involve local delivery of a bioactive molecule that would help control the immune reaction at the implant site. We are pursuing a bioprinting method of incorporating bioactive molecules onto implantable and planar electrodes. Bioprinting involves the adaptation of off-the-shelf (OTS) printer technology to the printing of bioactive molecules, cellular substrates, or viable cells. The bioactive molecules, cellular substrates, or viable cells therefore become a "bio-ink" which can be precisely appl! ied using standard printing software or modified print drivers.

Acknowledgment: University of Wisconsin Graduate School

**BIOGAUGES FOR CHARACTERIZING BIOMETRIC INTERFACE SYSTEMS**

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The primary goal of the BioGauges project has been to explore evaluation principles for biometrically-driven control interfaces. In order to accomplish this goal, we must first be able to measure and characterize inputs and outputs of BCI systems and components. Therefore, we developed methods to characterize and assess biometric transducer output in the form of discrete states, continuous levels, or spatial references. These methods allow us to estimate the controllability of BCI system and component designs that researchers have proposed and to assess their operation on various dimensions of control. The resulting information can then be used to improve BCI system designs.

In a collaborative study with the GSU BrainLab and the Neil Squire Society, we created the BioGauges toolkit to allow researchers to objectively measure and characterize the capabilities of a user with a biometric transducer. The BioGauges toolkit provides a series of "gauges", which are simple, instrumented control interfaces for both continuous and discrete inputs. A set of analysis tools allows the outputs of the gauges to be compared with other transducer outputs to obtain unbiased performance results. We demonstrated the BioGauges toolkit with a mu-based BCI transducer, the LF/ASD BCI transducer, and a Galvanic Skin Response transducer. Results show that biometric transducer output can be characterized using our toolkit. Future directions include designing gauges for spatial reference (P300, SSVEP) and other continuous control (SCP) systems.

In this poster, we present our methods for characterizing and assessing biometric transducers and demonstrate these methods using able-bodied subjects with two types of transducers: the LF/ASD transducer that produces self-paced discrete control signals and a GSR transducer that produces a continuous control signal.

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Key words: Biometric interfaces, BCI evaluation, transducer design.

# LOCALIZING NEUROPROSTHETIC IMPLANT TARGETS WITH FMRI: PREMOTOR, SUPPLEMENTARY MOTOR AND PARIETAL REGIONS

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Monkey recordings from premotor and parietal areas, including the parietal reach region (PRR), yield control signals for brain-machine interfaces to move a computer cursor or a robotic arm. Recently, there have been efforts towards transitioning the monkey findings to develop human brain machine interfaces for severely paralyzed patients, but as yet there is little precedent for finding human homologues of these high-level areas that have been functionally-defined in monkeys. Because severely paralyzed patients cannot execute real hand and arm movements, it is crucial to activate these human homologues using imagined movements to localize potential implant regions with fMRI. Utilizing event-related fMRI and a version of the delayed-reach task including both real and imagined pointing movements, we have identified regions involved in preferentially planning real and imagined points and not saccades. Our results in normal subjects reveal that such specialized regions exist in dorsal premotor cortex (PMd), the supplementary motor area (SMA), and medial posterior parietal cortex (PPC), where motor planning (target and effector known) activates these regions more than motor preparation (only effector known) or spatial attention (only target known). Imagined pointing did not elicit activity in primary motor cortex or the cingulate motor area, and point-related activity in these regions was limited to the movement period and not the delay period, reflective of involvement in point-execution and not point-planning. Thus, we have identified brain regions specific for planning real and imagined hand vs. eye movements, including PMd, SMA and medial PPC. Combining fMRI with image-guided neurosurgery may allow the extraction of neuroprosthetic control signals from these regions in paralyzed patients.

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# TOWARDS A 3 CLASS ASYNCHRONOUS BCI

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For a multi-class asynchronous BCI two important issues have to be considered: First the search for motor imagery related mental states best suited for classification and secondly the discrimination between motor imagery and rest (idling). Another problem is the online detection or elimination of artefacts, such as EOG or EMG.

Three able-bodied subjects took part in the online experiments with 2 or 3 bipolar EEG channels placed over the central region. Logarithmic band power features were extracted from the EEG and classified by LDA. In order to reduce the influence of EOG an online regression analysis was performed [1].

The mean online classification accuracy for 3 motor imagery tasks (left hand, right hand and foot or tongue,) was between 83% and 85%. The subjects were trained to operate the 3-class asynchronous spelling application named "Virtual Keyboard" [2]. Each subject succeeded in copy spelling of words composed of 3 to 5 letters with spelling rates varying from 1.0 to 3.4 letters/minute. The discrimination between rest and motor imagery achieved satisfactory results after minimizing the false positives (FP) by applying dwell time and refractory period [3]. From 40 possible hits the system was able to detect between 26 - 36 TP. The FP rate varied between 4 - 8 detections.

The results show that by using only 3 bipolar channels we can achieve satisfactory control for the asynchronous mode. However there are several questions which have to be addressed. The major question is whether 3 bipolar channels are enough to achieve higher classification accuracies between motor imagery and rest. Another problem is to find an appropriate evaluation strategy for the asynchronous operation mode and a proper definition of the performance measure.

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## ASSESSING NON-STATIONARITIES IN BCI DATA

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Nonstationarities and long-term changes of EEG-patterns can significantly affect the performance of a BCI system. Such long-term changes can have various origins (e.g. awareness, motivation, environment, but also effects due the BCI feedback etc), and are not easy to capture. In this work, the non-stationarities are studied in detail.

The short-time changes reflect mostly the class-related differences; almost all BCI-studies report these changes. These short-term changes are well represented by the time-course of the performance measure, for example Pfurtscheller et al (1998), Schlögl et al. (2002) reported time courses of the error rate and the mutual information, reflecting the class-related changes within each trial.

We applied this method to investigate the performance on various recording lengths. 1080 trials (3 sessions - 9 runs - 40 trials) from cue-based BCI data were investigated. These 1080 trials were partitioned into 27 segments with 40 trials each. From each partition, the time-course of the error rate, the mutual information and the kappa coefficients were calculated using AAR(3) parameters of two bipolar channels C3 and C4, Linear Discriminant Analysis (LDA) and a trial-based Leave-One-Out cross-validation was used. The implementation of the algorithms is available through BIOSIG (2005).

The results show the performance of different partitions of the data. The average performance of the 27 segments was statistically significant better than the classification result using all 1080 trials. This result suggests long-term changes in the data, which can not be modeled by a stationary classifier. Moreover, also the improvement in separability can be observed.

In summary, a method of testing for nonstationarities has been implemented and applied to BCI data.

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**MULTIFUNCTIONAL DEVICES - DRUG DELIVERY FOR IMPROVED NEURAL PROSTHESIS PERFORMANCE**

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Insertion of neural prosthetic devices into the brain produces characteristic biological reactive responses that our laboratory has defined using immunohistochemistry, confocal imaging and quantitative image analysis. Long-term use of these devices is compromised by cellular and vasculature encapsulation rendering the majority of the stimulating and recording electrodes non- functional. We are interested in determining events involved in initiating and maintaining these responses with the goal of developing intervention strategies to control such responses. Two approaches are being investigated. One strategy is testing devices fabricated with microfluidic channels for diffusion or infusion delivery. In order to better understand solute delivery, single channel silicon devices with a single port at the tip were fabricated using bulk silicon etching and surface micromachining techniques. Solute delivery was characterized in both in vitro and in vivo studies. In vitro delivery of 0.1 M Evans Blue into an aqueous solution and then agarose brain phantoms was tested for both repeatable and sustainable delivery. Evan Blue was visualized and measured using optical microscopy. For perfusion and infusion in vivo experiments, devices were backfilled with a cocktail containing membrane permeable (Hoechst stain) and membrane impermeable (propidium iodide) nucleic acid stains and then inserted into the neocortex of adult male Sprague-Dawley rats. Sustainable infusion rates from microfluidic implants were controlled through the use of a constant backpressure source. For infusion, one ml of the cell marker cocktail at a source pressure of either 5 or 10 psi, (infusion rates of approximately 15 and 30 nl/min) was infused approximately 1.5 mm below the pial surface. For diffusion, devices were inserted and left in place for the time needed to deliver 1 ml of cocktail determined from the average time used for the 5psi animals. Following fixation, 100-micron thick tissue slices were analyzed using widefield microscopy. Diffusion and infusion of Hoechst and propidium iodide provides a means of estimating the extent of damage that occurs around inserted devices due to insertion and/or pressure from infusion. The addressable tissue volume, and the extent of tissue containing apoptotic or necrotic cells can be determined via quantitative fluorescence analysis. Active delivery via low-flow infusion shows a significant improvement in the addressable tissue volume compared to diffusion mediated-delivery methods. In our second strategy hydrogels are being developed for neurotrophin delivery. Various modifications of HEMA hydrogels are being tested for solute capacity and delivery of functional protein using in vitro tests prior to insertion into the neocortex of rats. Using either one or a combination of these methods we will establish criteria for the control of reactive responses and improved long-term device performance.

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**PROOF OF PRINCIPLE INVESTIGATION: WORKING MEMORY SYSTEM A PROMISING CANDIDATE FOR BCI**

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Brain-Computer Interface research has mainly been focused on the primary motor regions for the translation of brain signals for controlling computer programs. However, the use of cognitive processes in brain machine control has recently gained interest, as such may be highly versatile in terms of multidimensionality control. We report on a proof of principle study for the use of the higher cognitive Working Memory (WM) system for BCI. A positive result would be accomplished if signal in the primary region of this system (dorsolateral prefrontal cortex, DLPFC) evidenced clear on- and offset, and controllable duration.

A mental calculation task was used, in which subjects had to decide whether a given equation was correct or incorrect. Equations came in one of three degrees of difficulty. Increasing difficulty was correlated with increasing reaction times, and should result in increased and/or sustained WM activation. 10 healthy subjects were tested with fMRI, and 2 epileptic patients with subdural electrodes for extra-operative seizure source localization were tested with both fMRI and ECoG.

Event related BOLD signals increased in amplitude and duration with increasing degree of difficulty within DLPFC in every individual. In the same region, ECoG recordings revealed that power in the gamma band (30-90 Hz) increased dramatically during calculation, and the duration corresponded to reaction time. Amplitude remained constant. These results indicate that the neural response to WM load can be readily detected, and is tightly coupled to duration of mental calculation.

In conclusion, we show here proof of principle that the spatial and temporal features of ECoG signal in DLPFC makes the WM system a promising candidate for BCI control. This system is strongly influenced by conscious control and exhibits promising features in terms of activity detection and a subjects  ability to self-regulate duration of activity.

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# REACHING AND RETRIEVAL IN 3D USING AN ANTHROPOMORPHIC ROBOTIC ARM CONTROLLED BY CORTICAL ACTIVITY FROM IMPLANTED MICROELECTRODES

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Single-unit activity in the motor cortex has been shown to represent natural arm movements. Several groups have shown that motor cortical activity can be used to drive prosthetic devices. It has been shown that intended movement velocity can be estimated from the firing rate of motor cortical cells using simple linear methods, such as our population vector algorithm (PVA). We have previously used a realtime implementation of a PVA to control a cursor in 3D virtual reality. Here we describe the use of a PVA that enables a monkey to control an anthropomorphic robotic arm in 3D space. With its own arms restrained, using only cortical signals, the monkey reaches and retrieves food rewards. The algorithm requires no prior knowledge of the relationship between neural activity and natural arm movement. Instead, the parameters are adaptively determined during brain control.

# ADAPTIVE ON-LINE CLASSIFICATION FOR BCI WITH STATISTICAL CLASSIFIERS

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Dp IEE

Usually, new classifiers or thresholds obtained from the data are applied and manually updated after an undefined period of time, which mainly depends on the experience of the operator. The aim of our adaptive on-line classifier was to automatically adapt to the changes in the EEG patterns of the subject and to deal with their long-term variations (non-stationarities).

In Graz, two different types of adaptive classifiers were tested in on-line experiments, ADIM and ALDA. ADIM is a classifier that on-line estimates the Information Matrix (ADaptive Information Matrix) to compute an adaptive version of the Quadratic Discriminant Analysis (QDA). ALDA is an Adaptive Linear Discriminant Analysis (ALDA) based on Kalman Filtering. Both classifiers were analyzed with different types of features, AAR parameters, logarithmic BP and the concatenation of both in one vector.

The design of the experiments followed another idea different than the classical. The traditional scheme consisted of training sessions without feedback, the computation of a classifier using this non-feedback data, and the performance of feedback sessions. The new adaptive system, allowed starting already in the most first session with feedback by using a predefined subject-unspecific classifier. From then on, it was on-line updated resulting in a subject-specific classifier. Therefore the subject could find a motor imagery strategy based only on the response of the system since the very first session.

The on-line updating algorithm was performed sample by sample. The classifier was adapted according to a trigger signal which estimated the best classification time using a moving average procedure. Then a delay was applied to the classification block in order to avoid over-fitting problems, because the upgraded classifier is applied to independent features.

The results of the experiments show that this BCI is a stable and robust system and that naive subjects are able to successfully control it.

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**DISCRETE CONTROL OF A ROBOTIC ARM WITH A P300-BASED BRAIN-COMPUTER INTERFACE**

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A P300-based brain-computer interface (BCI) detects the P300 component of the Event Related Potential (ERP) to produce control signals. The P300 is a well known component of the ERP that typically occurs about 300 - 800 milliseconds after a stimulus is presented. P300 BCIs have been tested in a variety of applications, including spelling, moving a cursor, or selecting icons. However, at the start of this study, P300-based BCIs had not been explored for controlling an external (physical) device. Therefore, it was unclear whether the distraction or electrical noise produced by the real-world feedback of such a device would impair a user's performance. This study demonstrates a P300-based BCI designed to allow a user to perform discrete selections, which then instruct a robot arm to perform the steps to make coffee. We measured the effects of the distraction of the moving robotic arm on the users' performance accuracy.

In this study, subjects viewed six icons that were associated with six different tasks the robot arm could perform, such as get milk, get coffee, or stir. A target icon was presented on a computer screen. The series of icons were then flashed in sequence, and the user was asked to count each time the target icon flashed while ignoring other flashes. Since only target events produce a large P300, the system could identify the target icon by determining which icon flash produced the largest P300. The robot arm then performed the task associated with that icon.

The study tested three different feedback conditions: a simple monitor condition with no external device connected, an interleaved condition in which the robot arm movement only occurred during pauses between groups of flashes, and a concurrent condition in which robot arm movement occurred simultaneously with flashes. The results showed that subjects were able to control the BCI effectively in all conditions, however there were slight performance differences. The concurrent condition and the monitor condition were comparable, and the subjects performed slightly worse in the interleaved condition.

It is unclear why performance was worse in the interleaved condition. The natural assumption is that performance would be worst during the concurrent condition, as the distraction created by the robot arm would be likely to avert attention and therefore affect performance. Instead, performance in the concurrent condition was comparable to the monitor condition, in which the robot arm created no distraction. Hence, it appears that the distraction created by the robot arm did not impair performance. This supports the hypothesis that P300-based BCIs can function effectively despite distraction.

# PROGRESS TOWARD A NEURAL INTERFACE FOR FEEDBACK CONTROL OF A MOTOR NEUROPROSTHESIS.

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Sensory feedback is required by biological motor control systems to maintain stability, respond to perturbations and adapt. Similarly, motor neuroprostheses require feedback to provide natural and complete restoration of motor functions. We have found that proprioceptive signals from the body's mechanoreceptors can provide a natural source of kinematic feedback and could be useful for prosthetic control. To this end, we report our progress in three areas: 1) obtaining reliable chronic recordings from multiple sensory neurons, 2) characterizing the relationship between limb kinematics and afferent firing rates, and 3) decoding limb kinematics from the ensemble of afferents.

To date, we have implanted a chronic recording array (9x4 grid, Cyberkinetics, LLC) into the L7 dorsal root ganglia of 5 cats. During the first 7-14 days after surgery, we are typically able to simultaneously record from 20 - 30 neurons, but recordings gradually worsen thereafter. Histology indicates that a ring of connective tissue (100 um thick) develops around each microelectrode and likely contributes to the degradation in recording quality.

Linear decoding models are used to study correlations between ensemble afferent firing rates and kinematic variables for the hindlimb. Results from 5 cats indicate that the firing rates of many afferents are highly correlated with kinematics expressed in both joint and endpoint space during walking at a range of speeds. Decoding performance is weakest for ankle joint angle (avg. $R^2 = 0.24$) and strongest for hip joint angle (avg. $R^2 = 0.7$). Decoding performance is also good for endpoint orientation angle (avg. $R^2 = 0.65$). However, there are high correlations ($r > 0.95$) between many pairs of endpoint and joint space kinematic variables, indicating that endpoint coordinates are tightly linked with joint coordinates. For example, the leg orientation angle (toe relative to hip) is highly correlated with the hip joint angle and both variables are strongly correlated with afferent firing rates throughout the step cycle.

Accurate reconstructions of hindlimb trajectory can be made using a linear filter with inputs from only a few neurons that are highly correlated with the kinematics. Neurons are selected for decoding based on their correlation with the kinematic variables. The coefficients for the linear filter are identified in a least-squares fit with 5-10 s of walking data (model training stage). The predicted and actual trajectories of separate walking data generally match well for walking at a range of speeds. The reconstructions account for 63 ± 22% (average across 3 joints ± S.D.) of the variance in joint angle and 72 ± 4% of the variance in joint angular velocities. Using endpoint coordinates, the VAF by the reconstruction is 79 ± 5% for position and 74 ± 8% for velocity variables. The largest error is in orientation angle and angular velocity predictions during late stance and early swing phases. In many cases, the accuracy of the predicted endpoint is better than from the corresponding joint-space reconstructions.

# FROM BITS TO WORDS: INFORMATION-EFFICIENT TEXT ENTRY

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Dasher is an open-source software application which uses a language model and a dynamic visual display to allow efficient entry of text. It is driven by continuous gestures (using mouse, joystick, head-tracker, gaze-tracker or breath control), or by discrete bit sequences from the user (for example using switches).

Users writing with Dasher are presented with a visual landscape of letters arranged down the right-hand side of the screen. To write the word "hello", the user points or steers in the direction of the "h", causing the display to zoom in on that region. Within the "h", another alphabet of letters appears, allowing selection of the second letter, "e", and so on. The amount of the display devoted to each each letter is determined by a language model. The right-hand side of the screen can be thought of as containing all possible sequences of text, laid out in alphabetical order. The user simply zooms in on the phrase they wish to write.

Dasher uses a language model, trained on text in the appropriate language and dynamically adapting itself to the user's writing, to estimate the probabilities of different sequences of letters, given those that the user has just written. Letters on the screen (and, implicitly, words and phrases) are given a size proportional to the probability that the user will wish to write them next. Thus, probable phrases are quick to write, with minimal user input. Improbable phrases (mis-spelled words, or gibberish) are always possible to write, but require more zooming, and hence more time and effort, from the user. Dasher implements the inverse of the arithmetic coding data compression method: it translates small gestures (short bit sequences) from the user into probable text strings.

Dasher has proved to be an effective means of text entry for users unable to use a conventional keyboard. When driven by a gaze-tracker, Dasher provides faster and more accurate results than an on-screen keyboard. In this poster, we review the theoretical basis for Dasher, the results from trials and feedback from current users, and our ideas for driving Dasher using BCI systems. There will also be the opportunity for you to try Dasher.

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**A TIME-FREQUENCY APPROACH FOR EEG-BASED BRAIN-COMPUTER INTERFACE**

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We have developed several novel algorithms based on time-frequency analysis of motor imagery (MI) related EEG rhythms for brain-computer interface (BCI) applications. The underlying neuronal coordination of MI tasks is characterized by desynchronization and/or synchronization of neural activity at the motor cortex during different time and frequency ranges, and consequently results in the decrease or increase of energy present in EEG rhythms. In our time-frequency analysis, the spatiotemporal EEGs are decomposed into time-, frequency- and spatial-components. The characteristic features of left- or right-hand MIs can be extracted and/or synthesized from these multi-dimensional components in training sets, and are used to classify MI tasks in testing data. The time-frequency analysis algorithm was tested using a public dataset consisting of nine human subjects. This approach has been further improved and tested in a human subject performing cursor control experiments using BCI2000. Our algorithm achieved 92.1% in the subject compared to the 83.3% accuracy of BCI2000. This promising pilot result suggests the time-frequency analysis approach we have developed may provide useful alternative for noninvasive BCI application.

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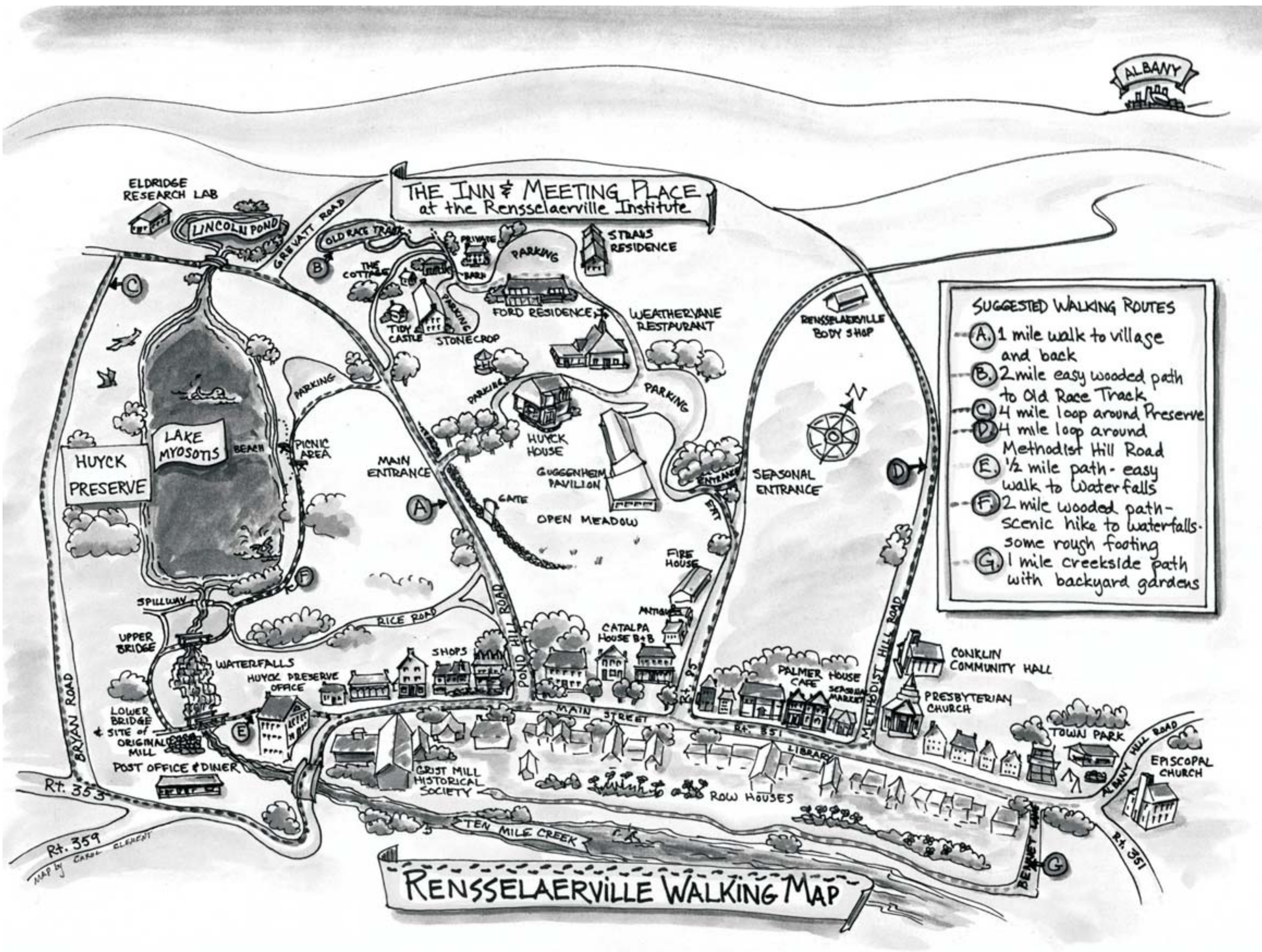
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STONECROP
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PARKING
HUYCK HOUSE
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GATE
OPEN MEADOW
SEASONAL ENTRANCE
EXIT
FIRE HOUSE
SPILLWAY
RICE ROAD
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SHOPS
CATALPA HOUSE B+B
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SEASONAL MARKET
CONKLIN COMMUNITY HALL
PRESBYTERIAN CHURCH
METHODIST HILL ROAD
LOWER BRIDGE & SITE of ORIGINAL MILL
MAIN STREET
Rt. 85
Rt. 851
LIBRARY
TOWN PARK
ALBANY HILL ROAD
EPISCOPAL CHURCH
POST OFFICE & DINER
GRIST MILL HISTORICAL SOCIETY
ROW HOUSES
BRYAN ROAD
Rt. 353
Rt. 359
TEN MILE CREEK
BENNET LANE
Rt. 351
MAP by CAROL CLEMENT
RENSSELAERVILLE WALKING MAP
SUGGESTED WALKING ROUTES
A. 1 mile walk to village and back
B. 2 mile easy wooded path to Old Race Track
C. 4 mile loop around Preserve
D. 4 mile loop around Methodist Hill Road
E. ½ mile path - easy walk to Waterfalls
F. 2 mile wooded path - scenic hike to waterfalls - some rough footing
G. 1 mile creekside path with backyard gardens