Development of Complex Curricula for Molecular Bionics and Infobionics Programs within a consortial* framework**

Consortium leader

PETER PAZMANY CATHOLIC UNIVERSITY

Consortium members

SEMMELWEIS UNIVERSITY, DIALOG CAMPUS PUBLISHER

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**Molekuláris bionika és Infobionika Szakok tananyagának komplex fejlesztése konzorciumi keretben

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NEURAL INTERFACES AND PROSTHESES

Neurális interfészek és protézisek

LECTURE 10

PHYSIOLOGICAL BASIS OF BRAIN-COMPUTER INTERFACE

Agy-számítógép kapcsolat fiziológiai alapjai

BALÁZS DOMBOVÁRI & GYÖRGY KARMOS

IN THIS LECTURE YOU'LL LEARN:

- General build-up of a Brain-Computer Interface (BCI)
- What is Amyotrophic lateral sclerosis disease?
- What kind of brain imaging techniques are good for BCI?
- Electrophysiological methods for BCI construction
- The physiology of the human brain
- Which types of brain electrical signals are good for BCI systems?
- Properties of EEG, ERP and ERD/ERS

DEFINITION

The brain electrophysiological signals can be used for communication with the external world as well as for manipulation of technical devices such prostheses and microprocessors. This type of biofeedback applications is named as ***Brain-Computer Interface (BCI).*** It is a multidisciplinary field comprising areas such as computer and information sciences, engineering, neuroscience, and psychology.

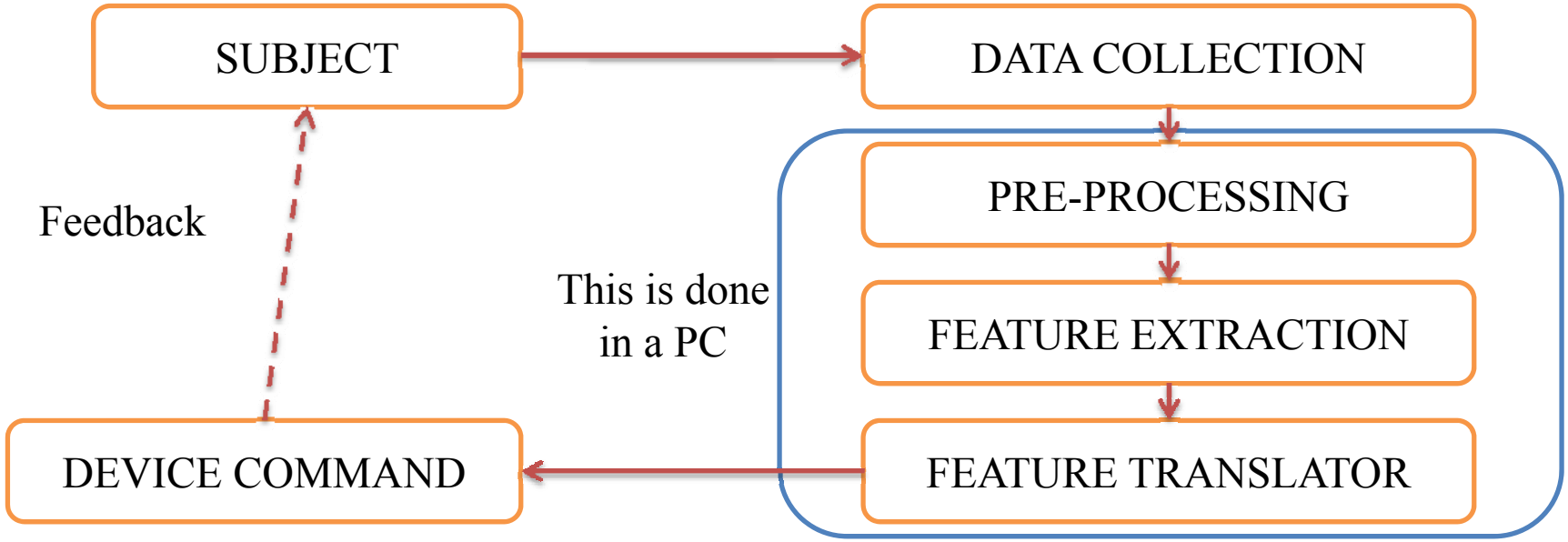
Assistive Device: the component of the BCI that directly interact with the objects or people in the environment.

Feature extractor: the component of the BCI that translates the input brain signal into a feature vector correlated to a neurological phenomenon.

Feature Translator: the component of the BCI that translates the feature vector into a useful control signal.

GENERAL BUILD-UP OF A BCI

In general, a BCI system comprises five stages: data collection, pre-processing, feature extraction, decision making or feature translation and device command.



AREAS OF BCI APPLICATION

There are diseases or pathological states when the muscle system of the patients is totally paralyzed. According to the early views BCI can help the patients to keep contact with the environment or control assistive devices only if there is no other physiological function that can serve this. If there are other ways (for example by eye movements or by blinking) these have to be preferred.

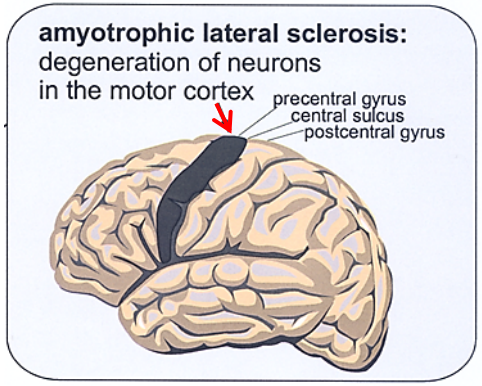
Nowadays as the BCI technology became more advanced, BCI may be used as part of a hybrid assistive system using traditional inputs. Here the BCI can be used as an additional input channel. (See Lecture 12)

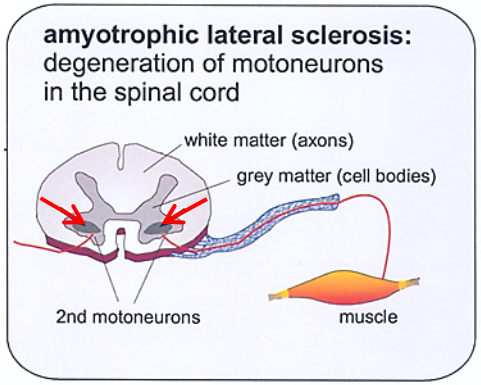
In the present course we deal only with those BCI devices that serve neuroprosthetic purpose. Recently series of commercially available BCI devices were developed for games etc. These are only shortly discussed in Lecture 12.

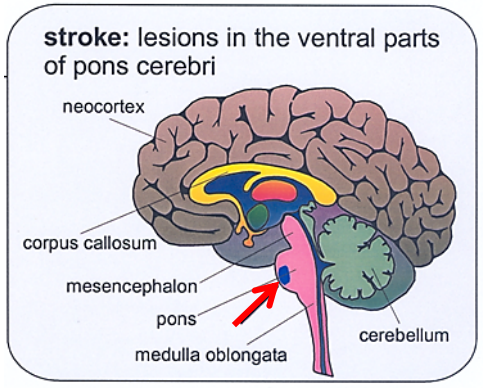
DISEASES IN WHICH BCI MAY HELP PATIENTS

There are degenerative diseases of the motor neurons in the central nervous system that result extended paralysis of the muscles. These are the *Amyotrophic lateral sclerosis (ALS)* and *Spinal Muscular Atrophy (SMA)*.

Paralysis of muscles of the whole body also can be caused by stroke or brain hemorrhage in the ventral parts of the pons cerebri, destroying the corticospinal motor pathways.







Lebedev & Nicolelis,TINS, 2006, 29: 536-546

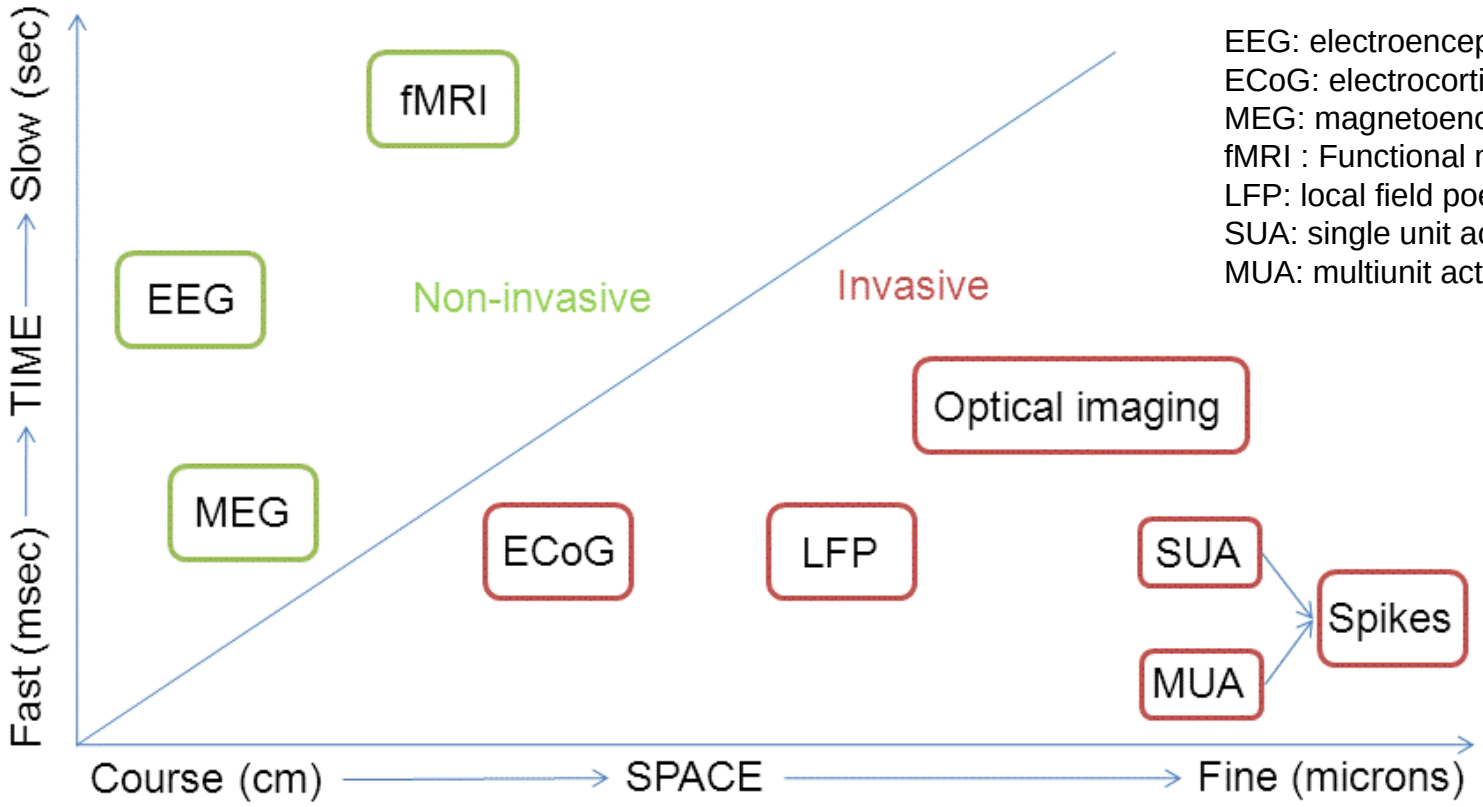
LOCKED IN STATE

Amyotrophic lateral sclerosis (ALS) *(also called as Lou Gehrig's disease)* is a progressive motor disease of unknown etiology that results in a complete destruction of the peripheral and central motor system affecting sensory or cognitive functions to a minor degree.

There is neither a standard treatment available, nor is a cure. Patients with ALS have to decide to accept artificial respiration and feeding after the disease destroys respiratory and bulbar functions for the rest of their life or die of respiratory problems. If they opt for life and accept artificial respiration, the disease progresses until the patient loses control of the last muscular response, which is usually the eye muscle or the external sphincter.

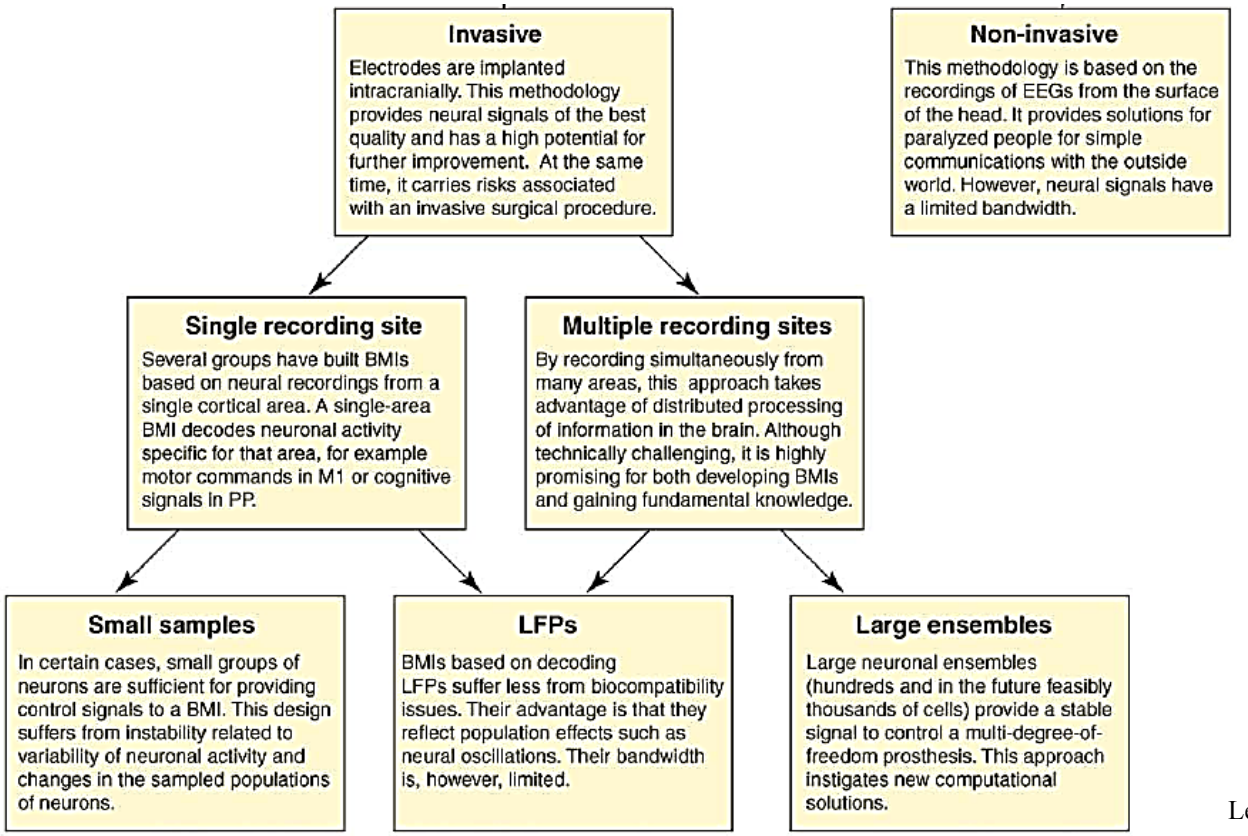
The resulting condition is called ***completely locked-in state (CLIS),*** if rudimentary control of at least one muscle is present we speak of a ***locked-in state (LIS)***.

WHAT KIND OF BRAIN IMAGING TECHNIQUES ARE GOOD FOR BUILDING BCI?



EEG: electroencephalogram
ECoG: electrocorticogram
MEG: magnetoencephalogram
fMRI : Functional magnetic imaging
LFP: local field poetntial
SUA: single unit activity
MUA: multiunit activity

WHAT KIND OF BRAIN IMAGING TECHNIQUES ARE GOOD FOR BUILDING BCI?



BMI, brain machine interface;
EEG, electroencephalogram;
LFP, local field potential;
M1, primary motor cortex;
PP, posterior parietal cortex.

Lebedev & Nicolelis,TINS, 2006

BRAIN ELECTRICAL SIGNALS USED FOR BCI

MACRO POTENTIALS:

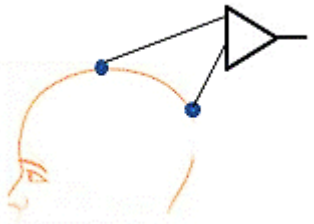
Noninvasive:

Electroencephalogram (EEG)

Event-related potential (ERP), P300 component

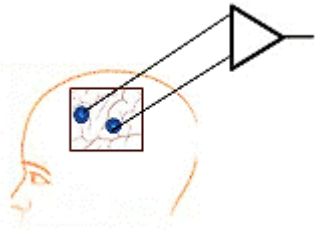
Steady state response (SSR), Visual SSR

Event related desynchronization/synchronization



Invasive:

Electrocorticogram (ECoG)

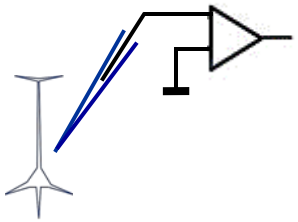


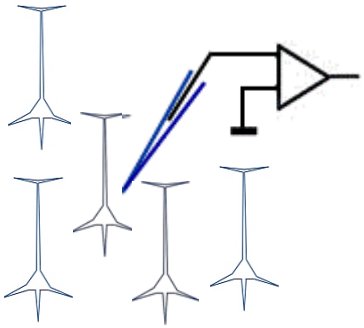
NEURONAL ACTIVITY:

Invasive:

Single unit activity (SUA)

Multiunit activity (MUA)





ELECTROPHYSIOLOGICAL METHODS FOR BCI CONSTRUCTION

Attempts to solve the problem of communication in patients who are paralyzed have led to several strategies that involve direct communication between the brain and a computer.

As we saw in the previous slide, the most usable techniques to build a BCI are electrophysiological methods from single cell recording through local field potential to scalp electroencephalogram.

In the next few slides our aim is to show how electrophysiological signals are generated in the brain and which biopotential changes are suitable for BCI use.

MEASURING BRAIN ACTIVITY

The brain is a dense network consisting of about 100 billion neurons. Each of these neurons communicates with about 10 thousands of others. Neurons communicate mostly via synapses by exchanging neurotransmitters or by sending electrical signals via gap junctions.

The electrical activity of neurons can be divided into two parts: action potentials (AP) and postsynaptic potentials (PSP). The PSP-s are summated in the neuron and if the membrane depolarization reaches the threshold level at the axon hillock, the neuron fires and an AP is initiated in its axon.

The electrical potentials recordable on the scalp surface are generated by low frequency summed inhibitory and excitatory PSPs of neocortical pyramidal neurons that form electrical dipoles between the soma and apical dendrites. These create the local field potentials in the cortex and extend to the scalp surface where they are recorded as EEG oscillations.

THE PHYSIOLOGY OF THE HUMAN BRAIN (CONT.)

Nerve cell APs have a much smaller potential field distribution and are much shorter in duration than PSPs. APs therefore do not contribute significantly to either scalp or clinical intracranial EEG recordings. Only large populations of simultaneous active neurons can generate electrical activity recordable on the scalp.

Because of the electrical properties of the brain tissue the action potentials of the neurons do not spread to large distance in the extracellular space. Therefore the action potentials of the neuron called unit activity can be recorded only by small tip size microelectrodes inserted close to the cell.

In most cases extracellular microelectrode records action potentials/spikes of more than one neuron. In this case the amplitude and shape of the unit spikes depend on the distance of the given neuron from the recording microelectrode.

THE PHYSIOLOGY OF THE HUMAN BRAIN (CONT.)

The cerebral cortex is the most relevant structure in relation to EEG measurement. It is responsible for higher order cognitive tasks such as problem solving, language comprehension and processing of complex sensory information. Due to its surface position, the electrical activity of the cerebral cortex has the greatest influence on EEG recordings. The functional activity of the brain is highly localized. This facilitates the cerebral cortex to be divided into several areas responsible for different brain functions.

Since the architecture of the brain is non-uniform and the cortex is functionally organized, the EEG can vary depending on the location of the recording electrodes.

PROPERTIES OF EEG

The EEG representing brain waves originateing from a multitude of different neuronal communities from various regions of the brain. These neuronal communities produce electrical contributions or components that can differ by a number of characteristics such as topographic location, firing rate (frequency), amplitude, latency etc.

The volumetric effect of the cerebrospinal fluid, skull and scalp result in a smearing of these electrical components that result in the scalp recorded EEG macropotential. Similar coherent electrical activity can be picked up in nearby electrodes.

The EEG activity above different regions of the scalp may reflect local activity but may also reflect activity of distant neocortical areas. These are called closed field and far field activities.

DESCRIPTORS OF EEG SIGNALS

This section highlights the many descriptors that are used with EEG recorded signals or its decomposed components to help in the categorization and description of complex brain activity.

Clinical electroencephalography uses a large number of these escriptors, particularly in the study of epilepsy, to facilitate accurate analysis. In relation to cognitive research the most important aspects of EEG activity are distribution, frequency, amplitude, morphology, periodicity but more importantly the behavioral and functional correlates. In summary, EEG requires a considerable level of experience to accurately identify and characterize the signals.

The table of the next slide summarize the descriptors used in EEG analysis.

Descriptor of EEG signals	Explanation	Characterisation examples
Morpology	Shape of the wave	Rhythmical (regular), Arrhythmical (irregular), Sinusoidal, Spindles Complexes, Spikes, Polyspikes, Sharp waves
Repetition	Defines the type of waveform occurrence	Rhythmic, Semi rhythmic, Irregular
Frequency	How often a repetitive wave recurs	Frequency Bands: Delta, Theta, Alpha, Beta
Amplitude	Measured in microvolts (μV) peak-to-peak or from the calibrated zero reference	Clinical reference: Low (< 20μV), Medium (20-50μV), High (>50μV), Amplitude assymmetry
Distribution	The occurrence of electrical activity recorded by electrodes positioned over different parts of the head	Widespread, Diffuse (generalised), Lateralised, Localised (Focal)
Phase relation	The relative timing and polarity of components of waves in one or more channels e.g. Do the troughs and peaks line up?	In-phase, Out of phase, Phase Angle
Timing	Relative occurrence of activity in time at different parts of the brain recorded by different channels	Simultaneous (Synchronous), Independent (Asynchronous), Bilaterally synchronous
Persistence	How often a wave or pattern occurs during a recording session	Index percentage (Proportion of time for which these waves appear in the recording), Poorly / Well sustained, High, moderate & low persistence
Reactivity	Refers to changes that can be produced in some normal and abnormal patterns by various maneuvers or functions	EEG alteration in response to: Closing the eyes, Hyperventilation, Visual or sensory stimulation, Changes in levels of alertness, Movements or movement imagination

EEG TECHNOLOGY

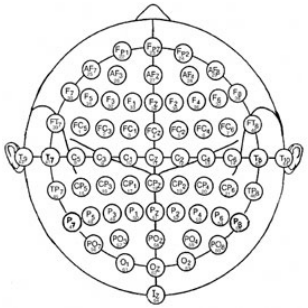
Silver/silver-chloride nonpolarizable electrodes are used for scalp EEG recording.

A special gel is applied between the electrode and the skin to assure good conductance. According to the international standards the impedance of the scalp-electrode interface must be below 5 kΩ.

The electrodes are placed to the scalp according to the „international 12-20 system”.

Frequency range, amplified by the modern digital EEG amplifiers can be positioned between DC or 0,1 Hz and 10 kHz.

Brain Products EEG BCI System



Extended 10-20 electrode system

EEG SIGNAL CLASSES FOR BCI SYSTEMS

For the purposes of BCI system design, there exist various EEG signal properties that discriminate brain function and hence can be used as an input mechanism to offer control or communication.

EEG signal properties for BCI systems can be categorized into one of the following groups:

1. Rhythmic and slow brain activity
2. Event-related potentials (ERPs)
3. Event-related desynchronization (ERD) and event-related synchronization (ERS).

RHYTHMIC BRAIN ACTIVITY

The human EEG potentials are manifested as aperiodic unpredictable oscillations with intermittent bursts of oscillations having spectral peaks in certain traditional bands:

- ***1-4 Hz (delta, δ),***
- ***4-8 Hz (theta, θ),***
- ***8-13 Hz (alpha, α),***
- ***14-30 Hz (beta, β) and***
- ***>30Hz (gamma, γ)***
- EEG potential changes below 1 Hz is called ***slow potentials***.

The band range limits associated with the brain rhythms, particularly beta and gamma, can be subject to contradiction and are often further sub-divided into sub-bands that can further distinguish brain processes.

RHYTHMIC BRAIN ACTIVITY (cont.)

Delta activity appears in adults only in deep sleep. It can be recorded in coma and may shows tumor or epi- or subdural hematoma.

Theta activity can be recorded light sleep in adult. Computer processing shows that theta may appear in temporal leads during cognitive tasks.

Alpha rhythm is characteristic in quiet wakefulness, with closed eyes, above the occipital area. This synchronized activity disappears at eye opening and the EEG amplitude decreases and the rhythm becomes desynchronized.

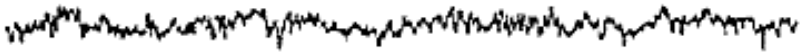
*Mu rhythm is an a*lpha like oscillation. It may appear above the motor cortex in motionless state. At self-paced movement it changes to desynchronized activity.

Beta activity is low amplitude fast rhythm. It is characteristic to alert state. Beta may appear in bursts above the motor cortex at the cessation of a self-paced movement.

Gamma activity is related to cognitive processes like attention and perceptional binding.

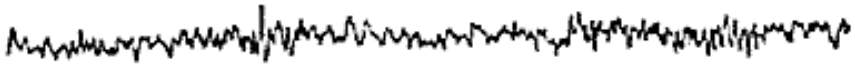
CHARACTERISTIC RHYTHMS OF THE EEG

Alertness: beta waves

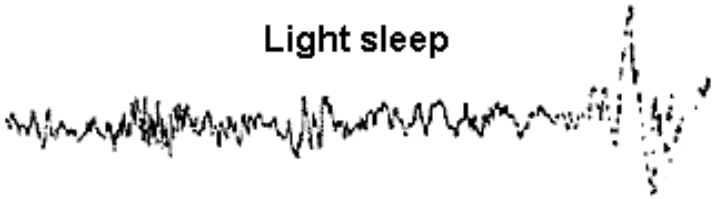


Relaxing: alpha waves

Sleeping: theta waves



Light sleep



Deep sleep: delta waves

EVENT-RELATED POTENTIALS (ERPS)

ERPs are time locked bioelectrical brain potential oscillations, elicited by a sensory stimulus, or associated with execution of a motor, cognitive, or psychophysical task.

Classification of ERPs:

Type of event:

- Sensory evoked potential
- Motor potential
- Event-related synchronization /desynchronization
- Steady state response
- Induced response

Classification of the components of ERP:

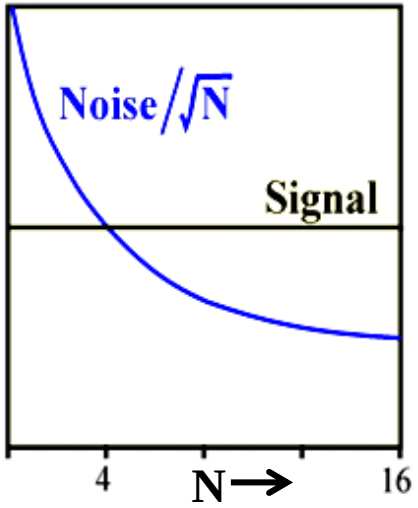
- *By latency:* Early-, Mid-latency-, Late- components
- *By nature of the evoking effect:* Exogenous components, Endogenous components

EVENT-RELATED POTENTIALS (CONT.)

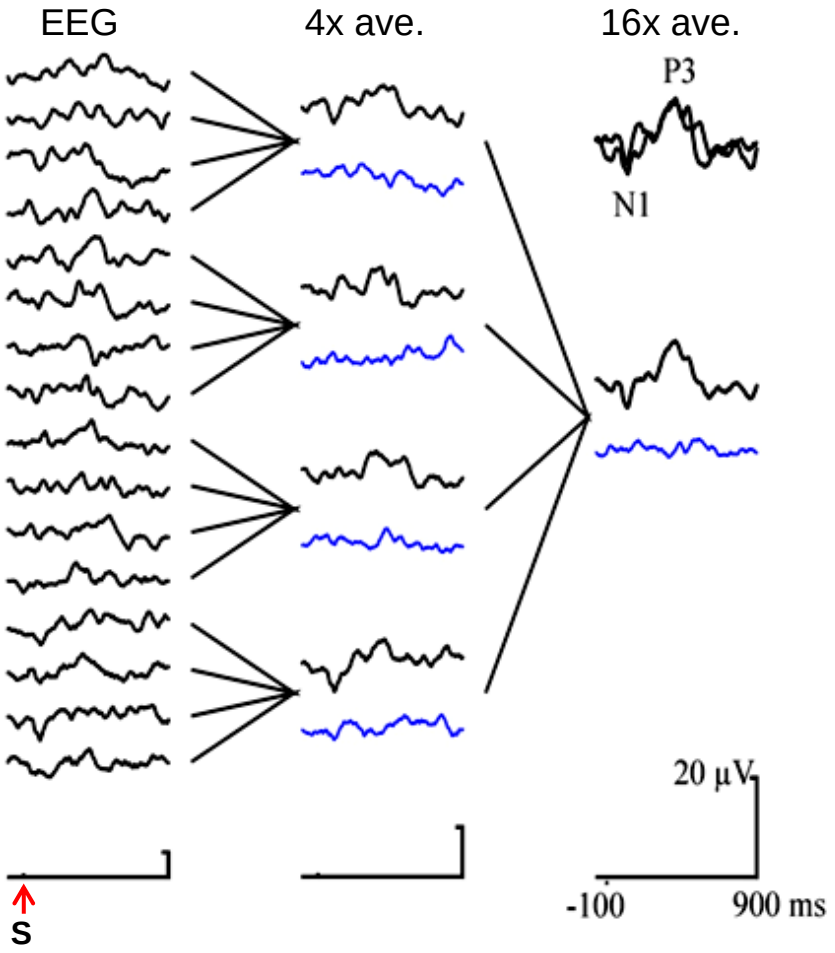
Amplitudes of ERP components are often much smaller than spontaneous EEG components, typically a factor of 10.

They are subsequently unrecognizable from the raw EEG trace. They can be analyzed by ensemble averaging EEG epochs time-locked to repeated sensory, cognitive or motor events. The assumption is that the event-related activity, or signal of interest, has a more or less fixed time delay to the stimulus, while the spontaneous background EEG fluctuations is random relative to the time when the stimulus occurred. Averaging across the time-locked epochs highlights the underlying ERP by averaging out the random background EEG activity, thus improving the signal-to-noise ratio. These electrical signals reflect only the activity which is consistently associated with the stimulus processing in a time-locked manner.

EFFECT OF AVERAGING ON THE S/N OF ERPS



It will take four times as many trials to make it look two times better.



EVENT-RELATED POTENTIALS (ERPS)

Exogenous components of the ERPs are usually the early, short latency components. Their parameters are determined by the physical properties of the evoking stimuli. They can be used to test the functional propeties of the sensory pathways.

Endogenous components of the ERPs provide a suitable methodology for studying the aspects of cognitive processes of both normal and abnormal nature, like in neurological or psychiatric disorders.

Mental operations such as those involved in perception, selective attention, language processing and memory, proceed over time ranges in the order of tens of milliseconds.

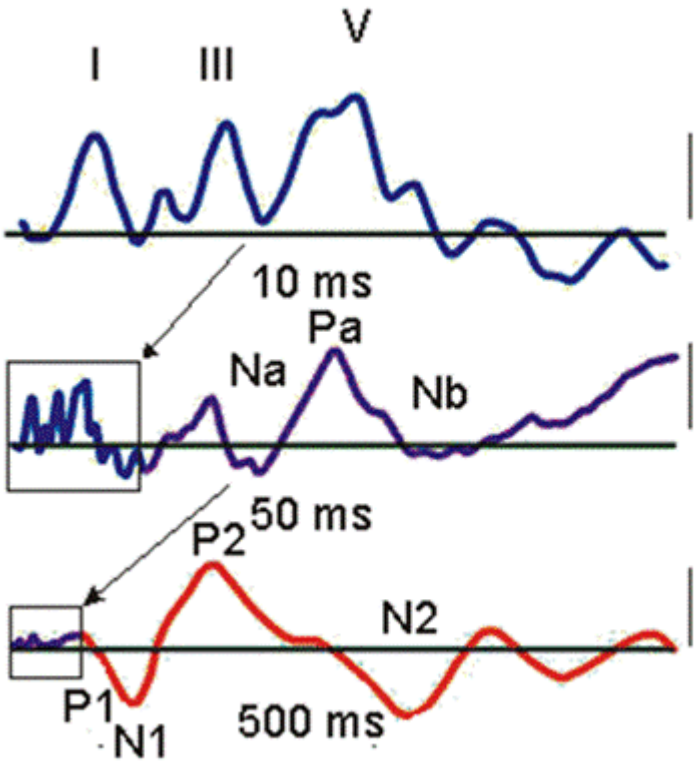
Whereas PET and MRI can localize regions of activation during a given mental task, ERPs can help in defining the time course of these activations.

CHARACTERISTICS OF EVENT RELATED POTENTIALS SHOWN ON THE AUDITORY ERP

Early components e.g. auditory brainstem evoked potential (BAEP)

Middle-latency components

Late components e.g. slow auditory response



Exogenous-

Mezogenous-

Endogenous-

components

EVENT-RELATED POTENTIALS (ERPS)

Exogenous components of the ERPs are usually the early, short latency components. Their parameters are determined by the physical properties of the evoking stimuli. They can be used to test the functional propeties of the sensory pathways. (e.g. BAEP)

Endogenous components of the ERPs provide a suitable methodology for studying the aspects of cognitive processes of both normal and abnormal nature, like in neurological or psychiatric disorders. (e.g. P300)

Mental operations such as those involved in perception, selective attention, language processing and memory, proceed over time ranges in the order of tens of milliseconds.

Whereas PET and MRI can localize regions of activation during a given mental task, ERPs can help in defining the time course of these activations.

EVOKED POTENTIALS (EPS)

Evoked potentials (EPs) are a subset of the ERPs that occur in response to certain physical stimuli (auditory, visual, somatosensory etc.).

They can be considered to result from a reorganization of the phases of the ongoing EEG signals.

The EPs can have distinguishable properties related to different properties of the stimuli, for example, Visual Evoked Potential (VEP) over the visual cortex varies at the same frequency as the stimulating light.

There are many successful EP based BCI systems that utilize VEPs, or P300s as inputs.

If repetition rate of the stimuli are increased above a certain rate EPs merge into a sinus like oscillation. It is called ***„steady state response" (SSR)***.

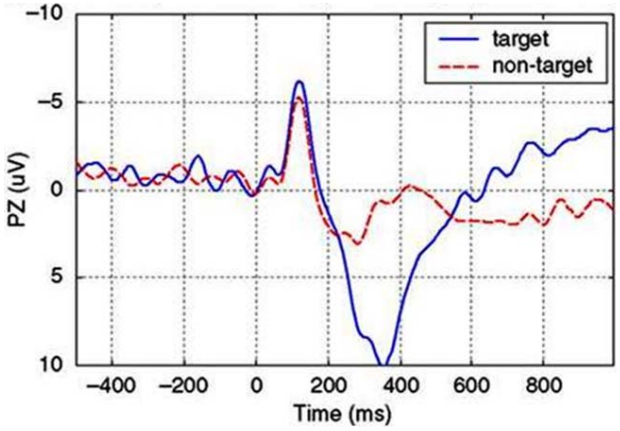
Visual SSR (VSSR) also was demonstrated as succesful signal for BCI.

ODDBALL PARADIGM

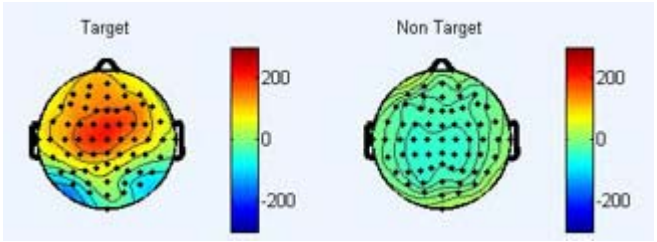
In ERP research often used paradigm is the so called ***„oddball paradigm”***

The subject is presented with two types of stimuli. One is a frequently occurring, more common stimulus (called standard or non-target) interleaved by infrequently, rare (‘oddball’) stimuli. The ERPs elicited by the standard and deviant stimuli are compared.

The oddball paradigm can be *passive*, if the subject has no task to respond to either of the stimuli. In *active* oddball paradigm the subject is asked to indicate the occurrence of the rare (target) stimuli by counting or by pressing a button.



P300 in auditory oddbal paradigm



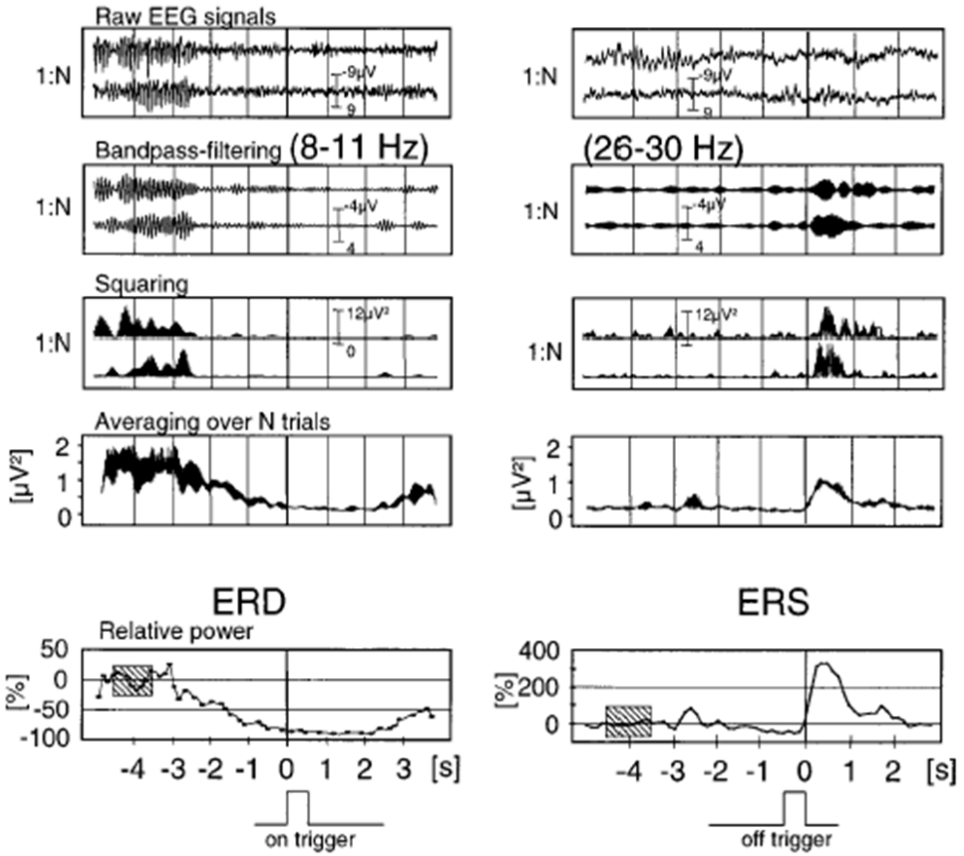
Distribution of P300 above the scalp

EVENT-RELATED DESYNCHRONIZATION AND SYNCHRONIZATION (ERD/ERS)

In 1977 Pfurtscheller and Aranibar first quantified event-related desynchronization (ERD). It appears above the motor area of the neocortex at self paced movements. ERD is amplitude attenuation and ERS is amplitude enhancement of a certain EEG rhythm.

In order to measure ERD or an ERS, the power of a chosen frequency band is calculated before and after the event over a number of trials. The average power across a number of trials is then measured in percentage relative to the power of the reference interval. The reference interval can be an arbitrary period prior to the event representing a period of inactivity or rest. The ERS is the power increase (in percent) and the ERD is the power decrease relative to the reference interval that is defined as 100%. ERD/ERS measurements selected over specific frequency ranges are typically used to produce a spatio-temporal map to visualize the functional behavior of the brain.

PROCESSING OF ERD AND ERS



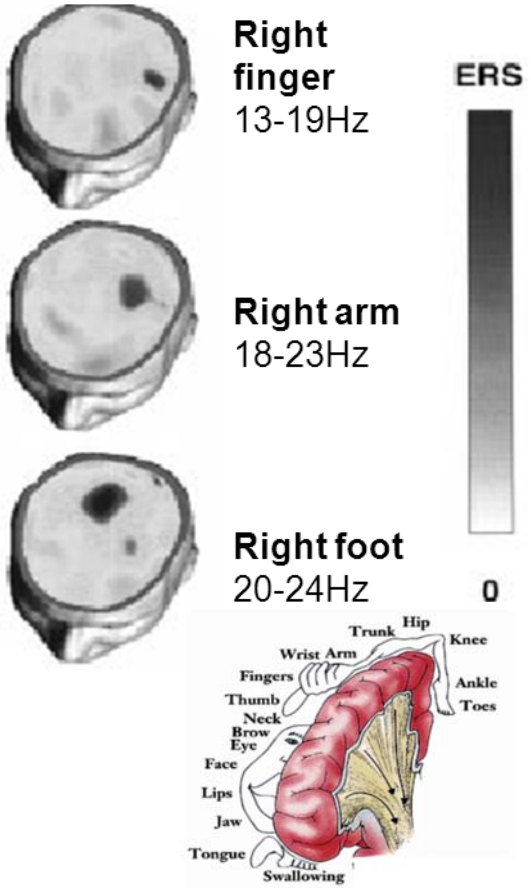
Pfurtscheller and Lopes da Silva, Clin. Neurophysiol. 1999

Alpha ERD and beta ERS to repeated flexion of the index finger. ERD appears before and during movement, ERS appears after the termination of the movement.

Processing steps:

Bandpass-filtering
Squaring
Averaging
Calculating relative power change

LOCALIZATION OF ERD/ERS ABOVE THE MOTOR CORTEX



The localization of ERD as well as the ERS corresponds to the cortical representation of the given movement.

ERD/ERS appear not only to the execution of a movement but also to the movement imagination. This means that it can be used in totaly paralized patients as input to BCI systems.

Pfurtscheller and Lopes da Silva, Clin. Neurophysiol. 1999

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REVIEW QUESTIONS:

- What is brain-computer interface?
- What is BCI feature extractor?
- What are the main application areas of the BCIs?
- Describe the symptoms of the Amyotrophic lateral sclerosis.
- What is „locked in state”?
- List the types of electrical signals that are used in BCIs.
- Which are the main descriptors of the EEG?
- Describe the main types of ERPs.
- What is the oddball paradigm?
- What are the main features of the ERD/ERS?