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Brain-Computer Interface

Christoph Guger, CEO
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g.tec medical engineering GmbH
Graz & Linz, Austria

biomedical engineering program


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Emperor's castle
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DENMARK
NETHERLANDS
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HUNGARY
FRANCE
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ITALY
GREECE
TURKEY
Mediterranean Sea

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g.tec – “accelerate your biosignal research”

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company fields

- bio-engineering, medical electronics (bio-electricity)
- developing and offering hard- and software products for biosignal research (**single cell activity**, **EEG, ECoG**; muscle cells: **ECG, EMG**; other tissue: **EOG**, ...)
- performs user specific adaptations and developments
- mainly based on rapid prototyping environment under *MATLAB/Simulink*

company description

- private company, located in Graz and Schiedlberg (Linz), Austria
- inter-disciplinary team (biomedical- , telematics engineers, psychologists)
- customers: universities, university hospitals, R&D departments, industry

Cooperations

EU IST– Virtual Reality PRESENCCIA

Tracking subject responses in the VE by neuro-physiological measurements: building better VE, therapy applications for patients with anxiety psychosis, ...

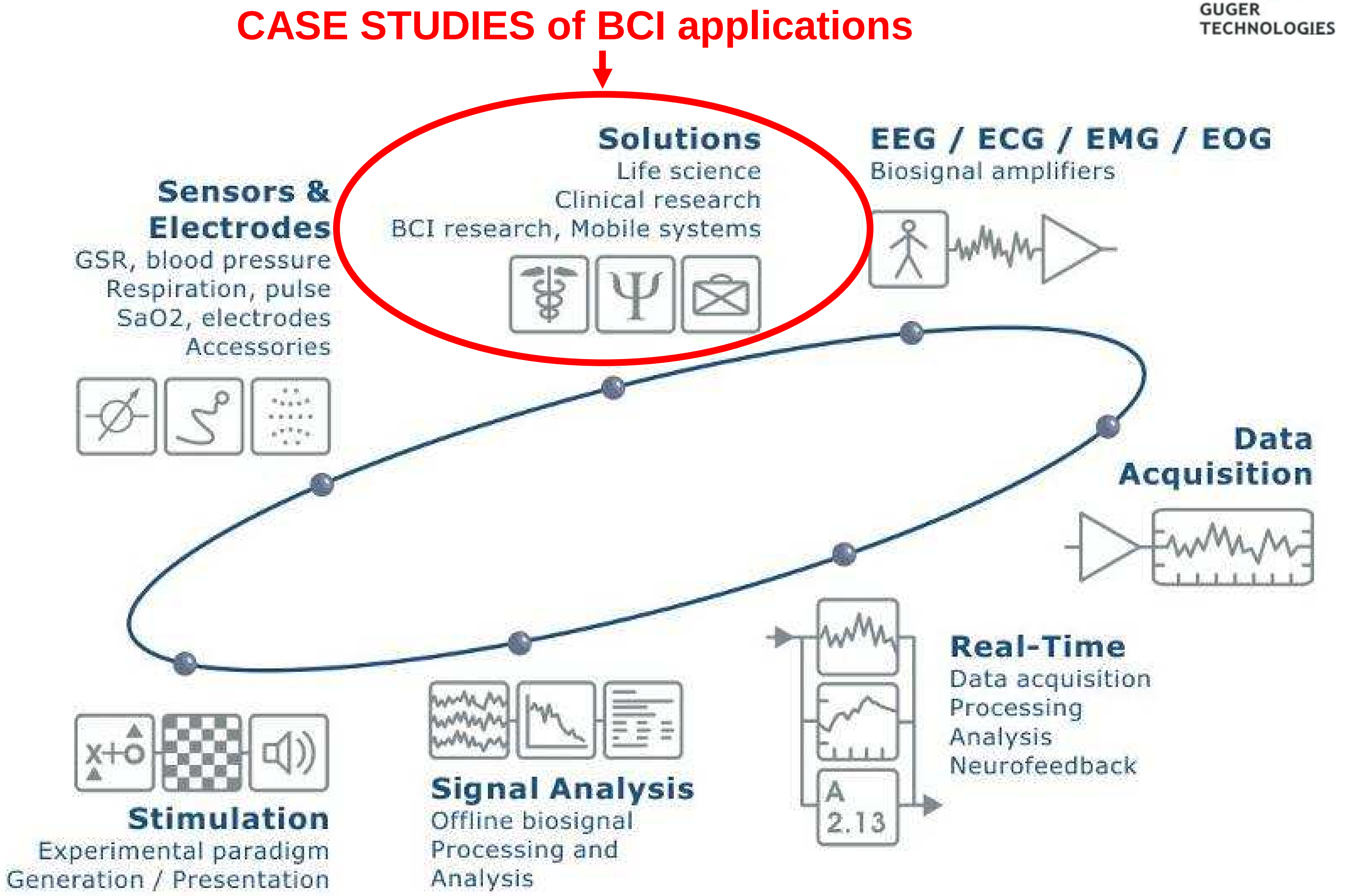
- Virtual Environments and Computer Graphics, UPC, Barcelona
  Mel Slater, Chris Groenegress

- University of Technology Graz, Austria
  Robert Leeb, Gert Pfurtscheller

- Insituto de Neurociencias, UMH, Alicante, Spain
  Mavi Sanchez-Vives

- UPF Barcelona
  Paul Verschure

Range of Products



Content

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Brain Computer Interface

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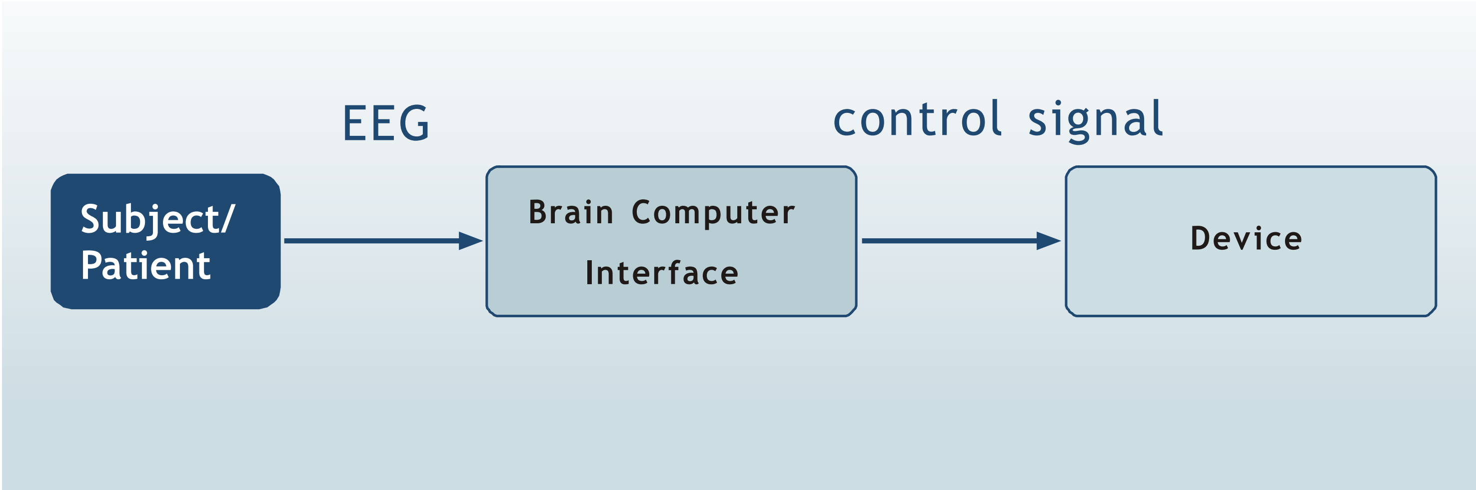
III) Closed loop Applications:

Brain-Computer-Interface (BCI) in VR



… establishes the only communication channel without using any muscle activity …

a BCI **transforms EEG** signals into **control signals**

HCI – Human Computer Interface

DBI – Direct Brain Interface (University of Michigan)

TTD – Thought Translation Device (University of Tübingen)

Applications of a BCI in patients

- patients with **amyotrophic lateral sclerosis** (ALS)
- **locked-In Syndrome** (LIS) to communicate
- patients with **amputations** to control a robotic limb
- patients with **spinal cord lesions** to control a FES device or a wheelchair
- gaming
- composing music
- walking through VE, controlling VE

Some examples of BCI applications

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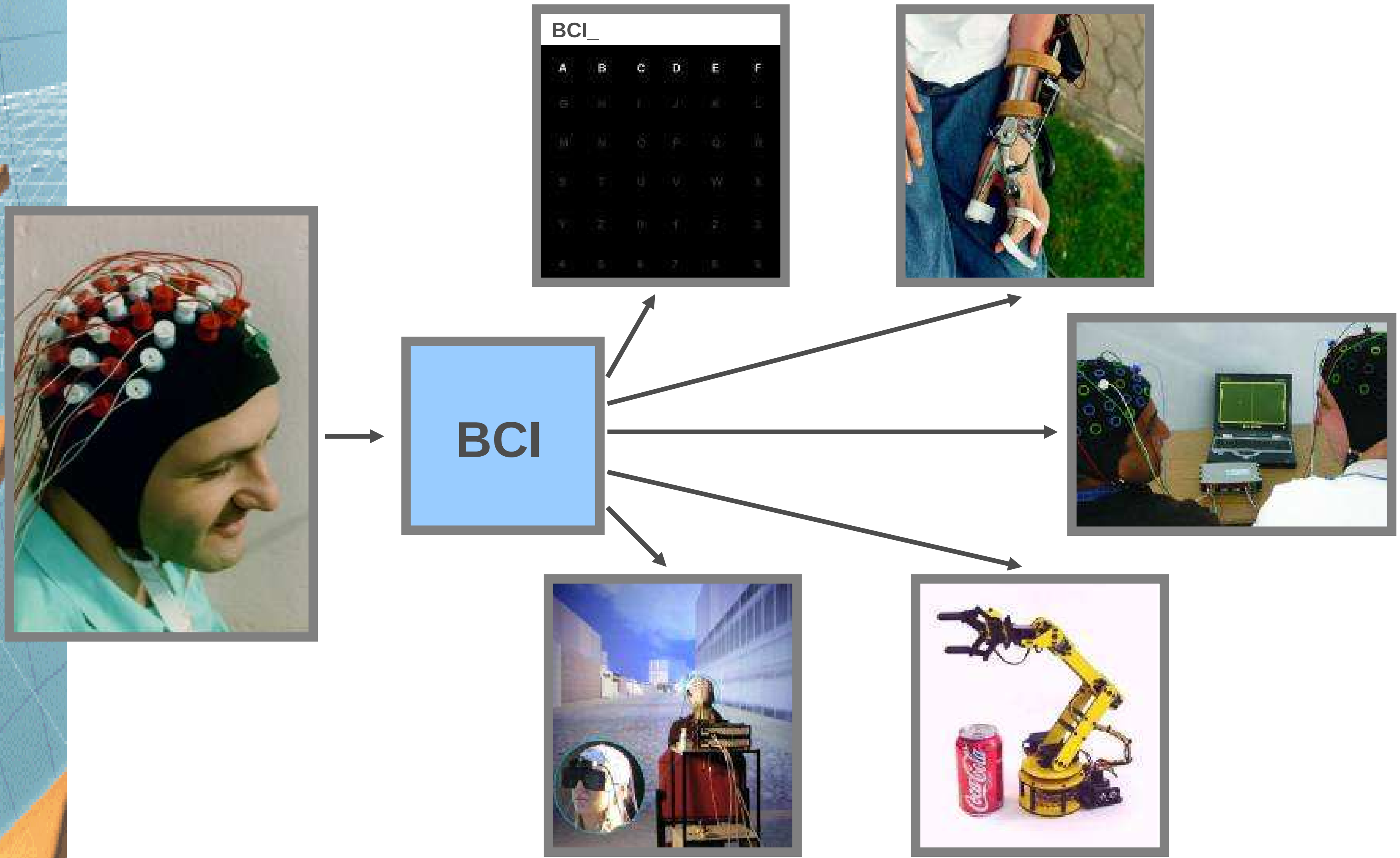

Leeb et al., Computational Intelligence and Neuroscience, 2007 (doi:10.1155/2007/79642)

Applications of a BCI in subjects/patients

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Potential users worldwide

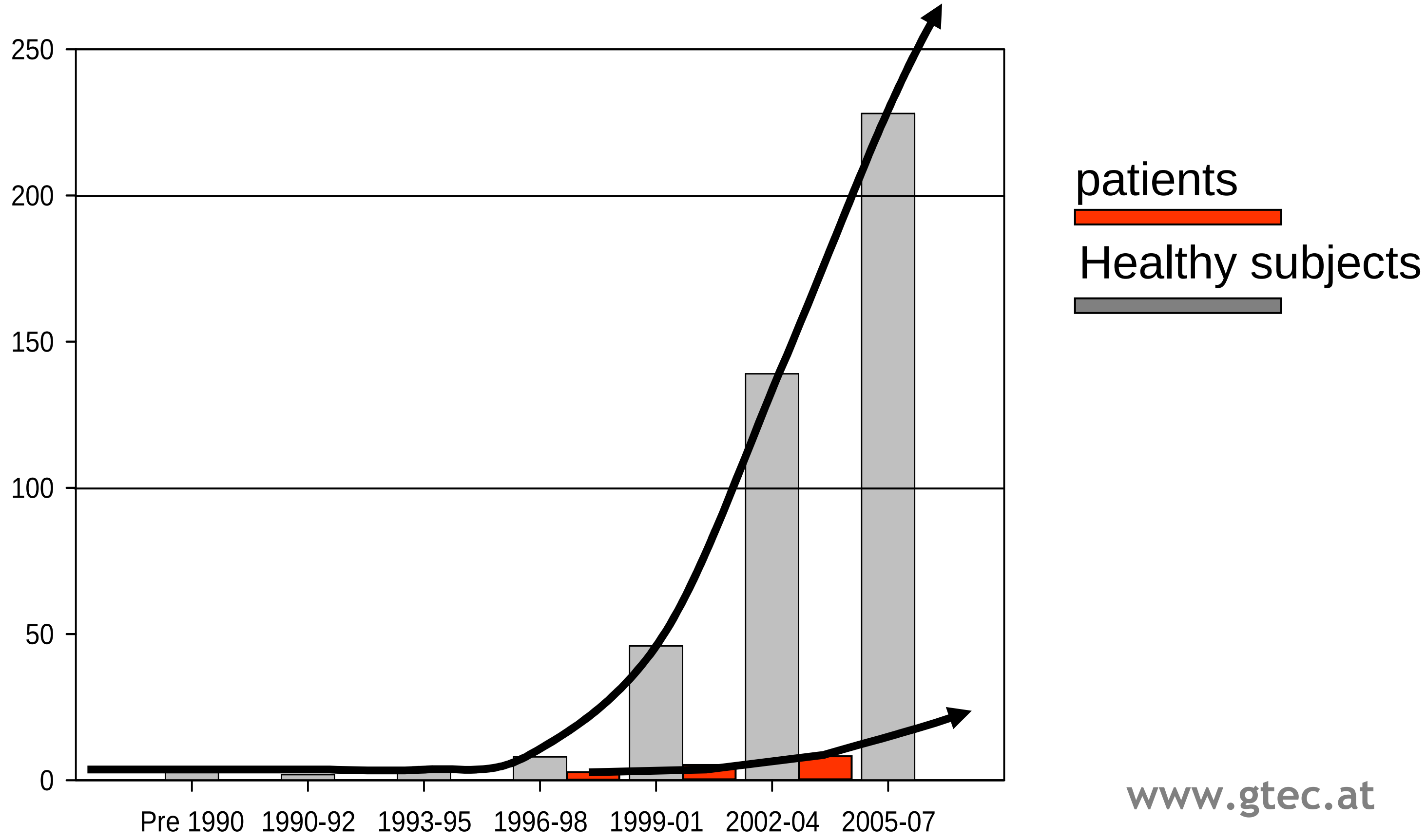
Cerebral palsy	– 16,000,000
Brainstem stroke	– 10,000,000
Other stroke	– 60,000,000
Spinal cord injury	– 5,000,000
Postpolio syndrome	– 7,000,000
Amyotrophic lateral sclerosis	– 400,000/3,000,000
Multiple sclerosis	– 2,000,000
Muscular dystrophy	– 1,000,000
Guillain-Barre syndrome	– 70,000

Adapted from Vaughan, private conversation

Evolution of BCI research

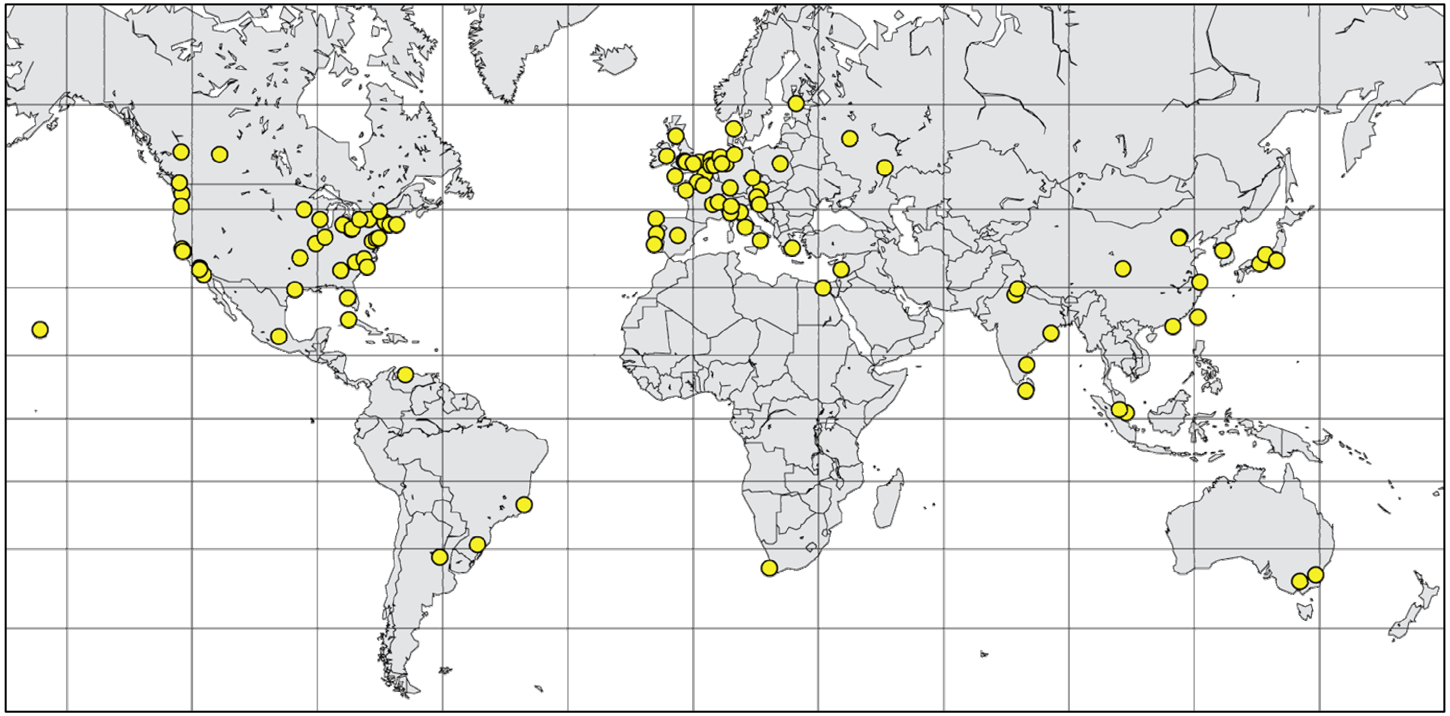
- 1995 ~ 5 labs active in BCI research, first demonstrations
- 2005 > 70 laboratories active all over the world
- 2007 > 120 laboratories involved in BCI research

Growth of BCI publications in peer-Reviewed Papers



Evolution of BCI research

• "BCI Activity Map" > 120 sites



Adapted from Schalk et al.

Evolution of BCI research

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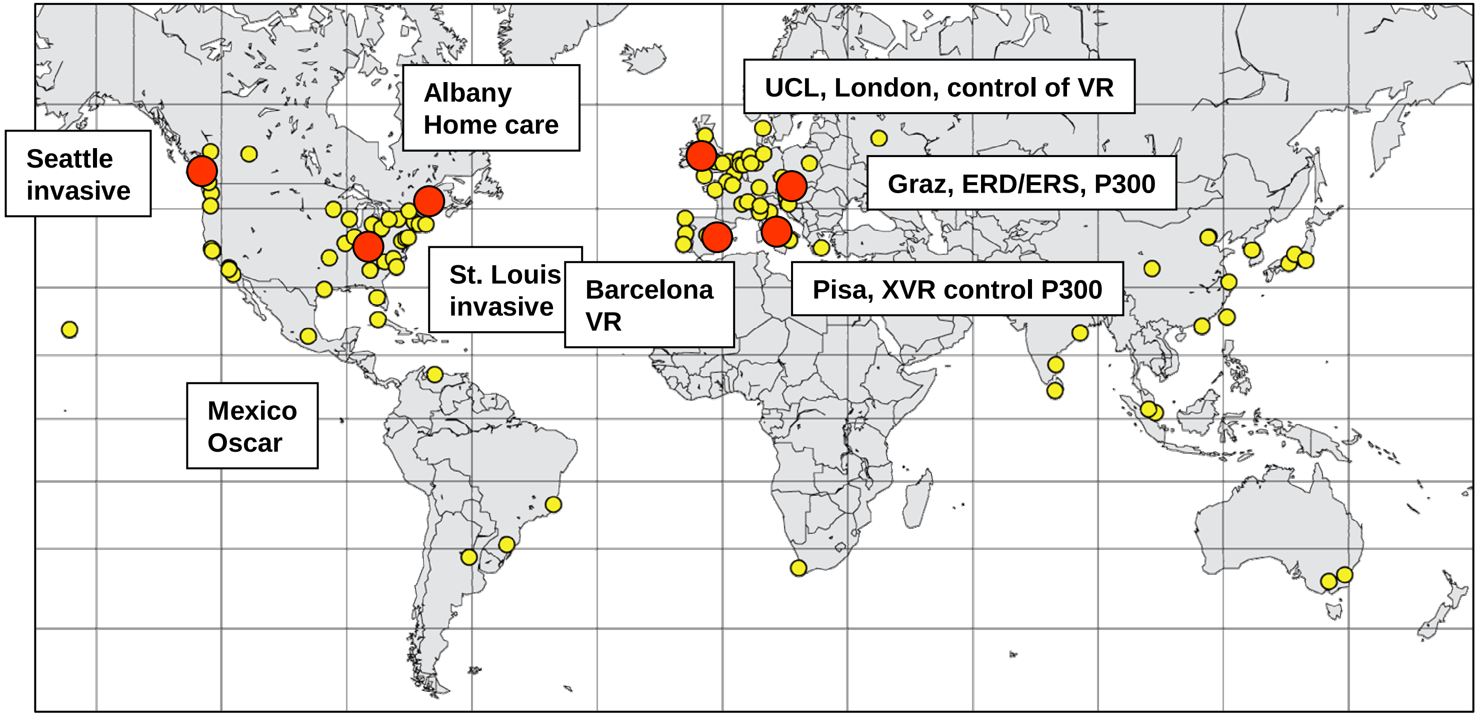
- Case Studies from



Case studies 2007

Changes of brain electrical activity and mental strategies

- Slow cortical potentials (anticipation tasks)
  DC-derivation, artifact problem, difficult strategy, feedback method

- Steady-State Evoked potentials (SSVEP, SSSEP)
  Flickering light with specific freuqency

- Event-related, non-phase-locked changes of oscillatory activity ERD/ERS (**motor imagery tasks**)
  Changes of mu-rhythm, alpha activity and beta activity over sensorimotor areas, imagination of hand- ,foot-, tongue- movements

- **Evoked potentials (focus on attention task)**
  Thalamic gating, various methods of stimulation (visual, tactile, electrical, auditory, ...), P300

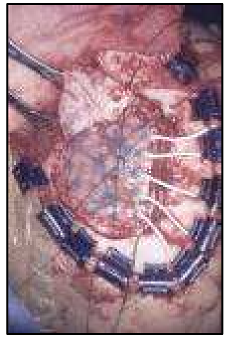
Measurement of brain signals

Multi-channel analysis system with
derivations simultaneously and also directly in the brain

- *Electroencephalogram*

  non-invasive

  bad spatial resolution



- *Electrocorticogram*

  direktly measured on brain's surface

  good spatial resolution

- *Micro-electrode arrays*

  implanted into the brain

  best signal quality

Excursus: Measuring brain activity

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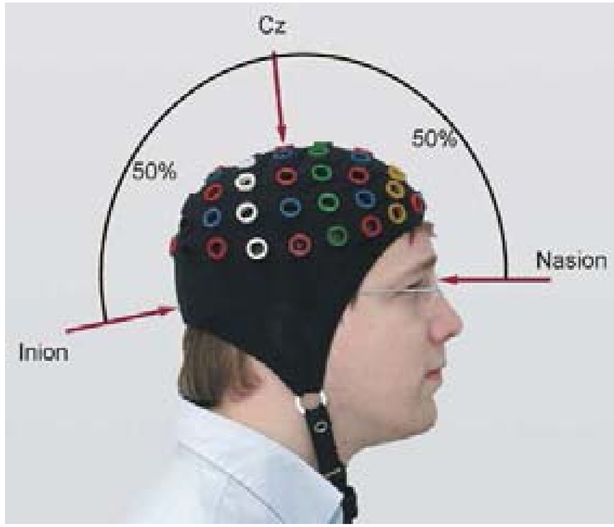
Electroencephalogram (EEG)

small electrodes (#1 - #256) attached to the surface of the scalp

place electrodes at certain predefined positions according to the "international 10/20 system"

EEG amplitudes: **5 – 100 uV**

EEG frequencies: **1 – 40 Hz**



EEG: non-stationary time signal
varies greatly between subjects
low signal-to-noise ratio

- spatio-temporal patterns
- non-invasive

Excursus: Measuring brain activity

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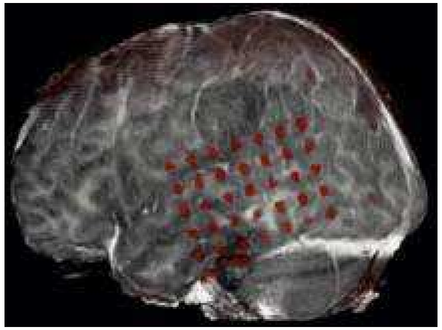
Electro-corticogram (ECoG)

4 mm diameter

~ 100 electrodes


modified from University of Michigan

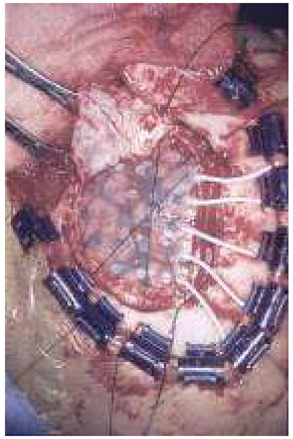
EEG amplitudes: **0.5 mV**

EEG frequencies: **1 – 100 Hz**

- **resolution considerably better than EEG**
- **provides opportunity for multi-channel control**
- **more direct correlation to activity**

invasive

limited study opportunities


modified from University of Michigan

Influencing components

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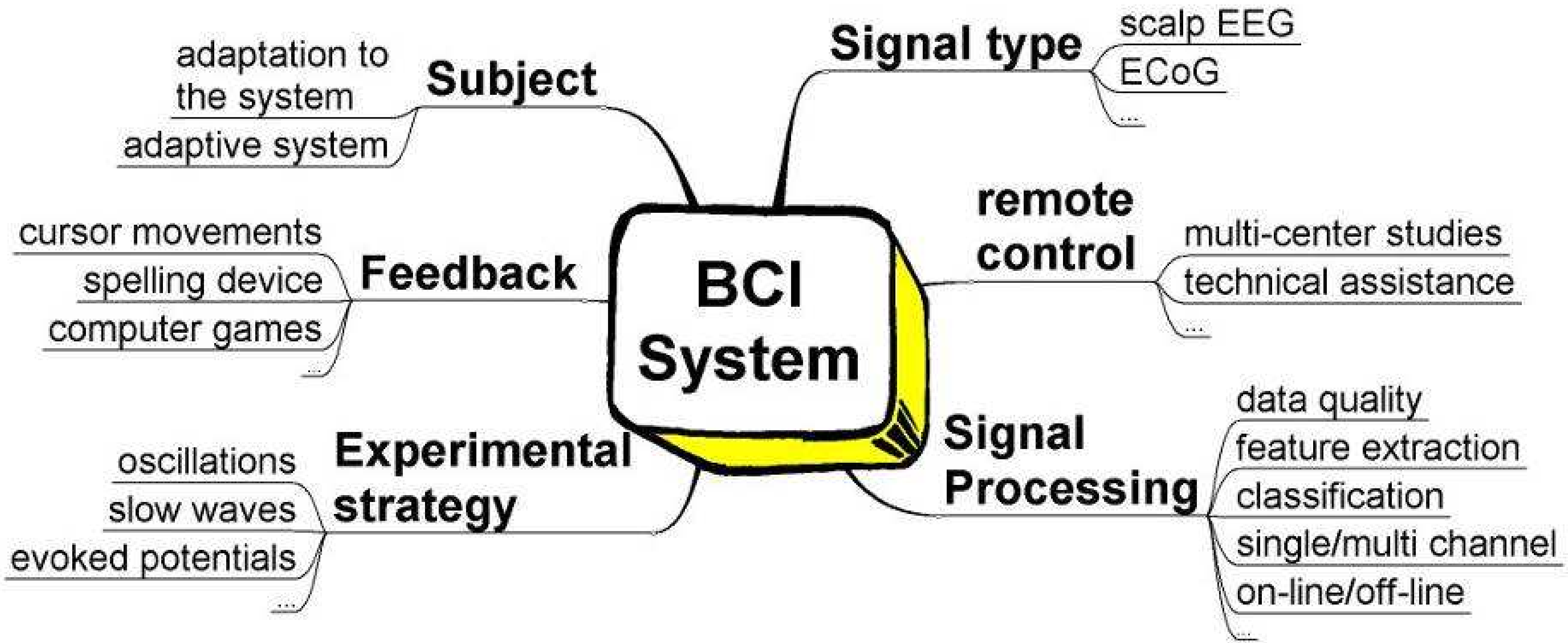
adaptation to subject ← → **technical issues**



Steps in BCI development

Step 1: Selection of parameter estimation and classification algorithms

Step 2: Implementation of the algorithms

Step 3: Off-line simulation

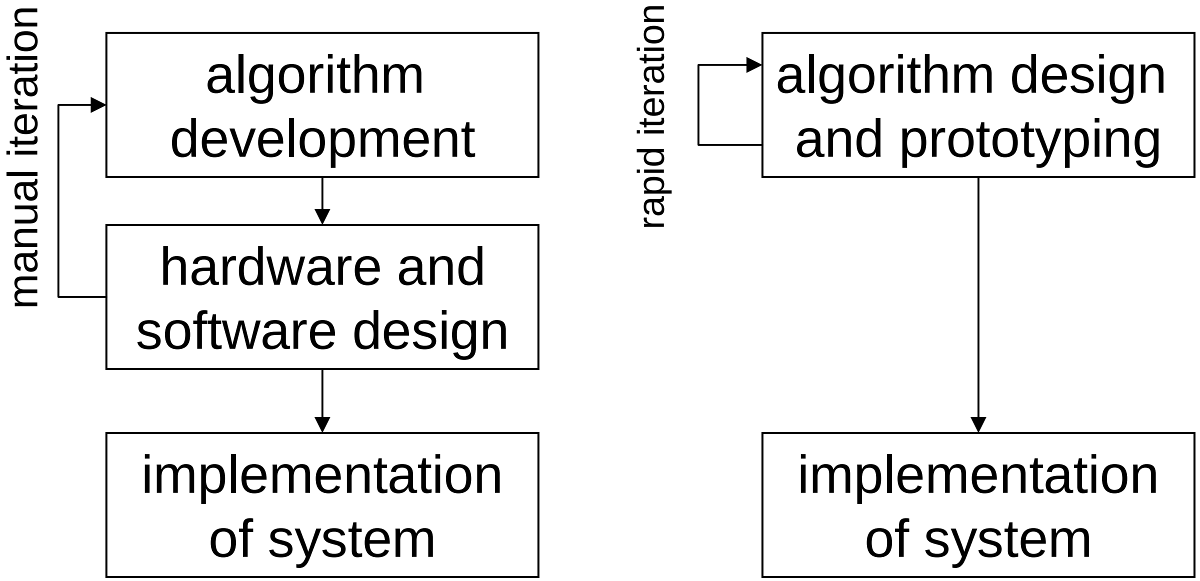
Step 4: Connection to the real world

Step 5: Real-time code generation

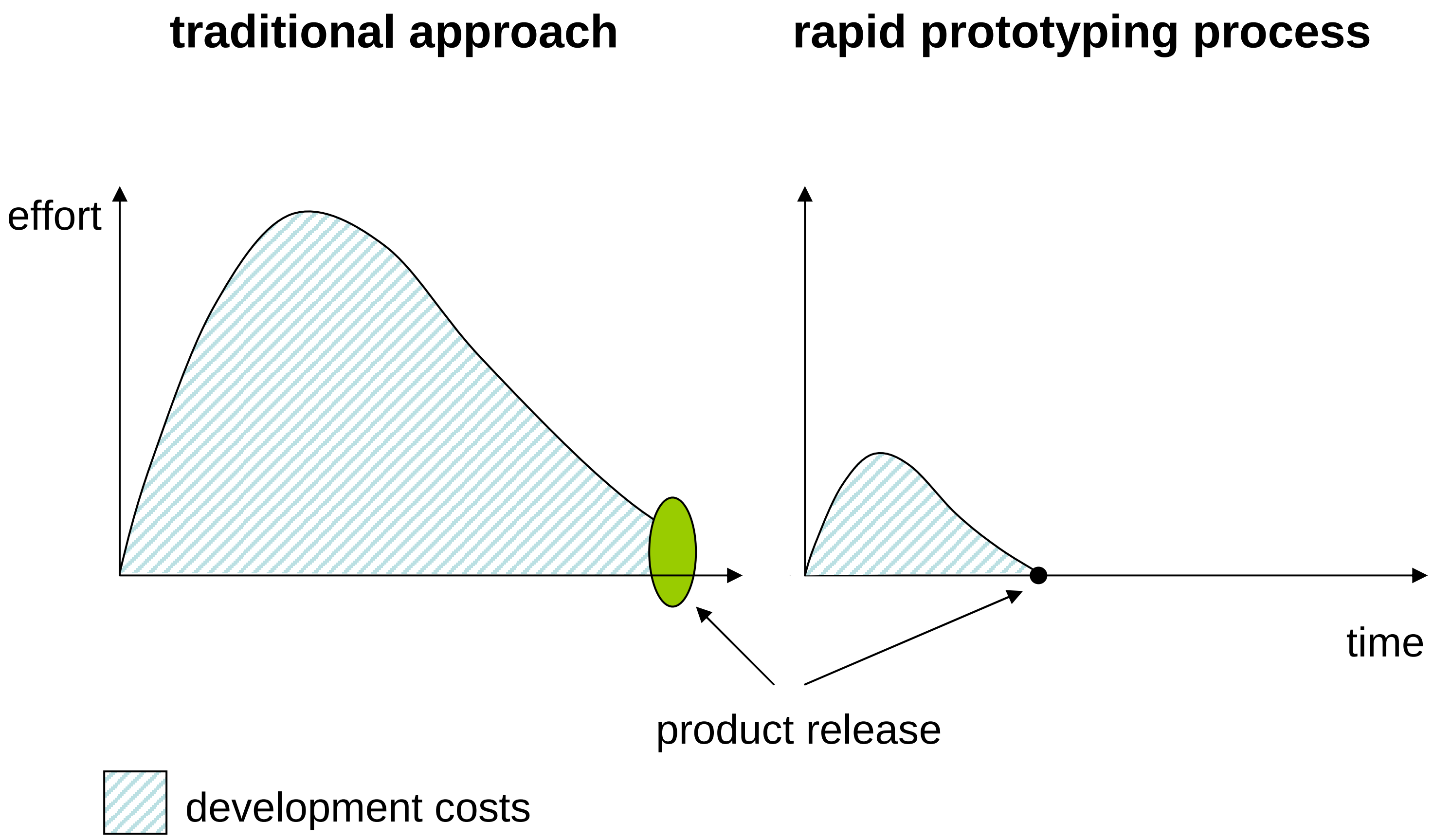
Step 6: Real-time tests

Why Rapid Prototyping?

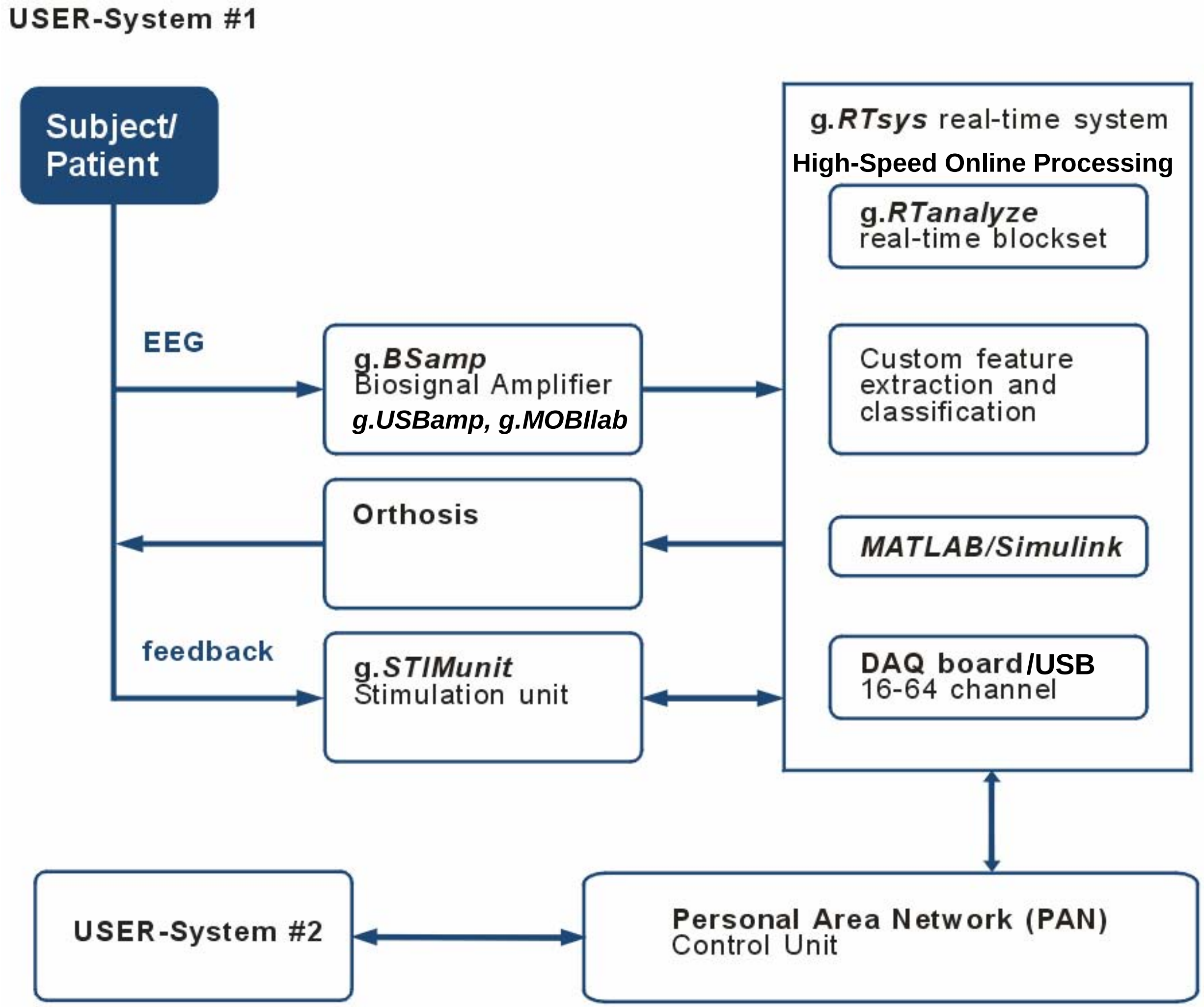
traditional approach **rapid prototyping process**



Why Rapid Prototyping?



Closed loop system g.BCIsys



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Requirements to successfully run BCI experiments

Product range

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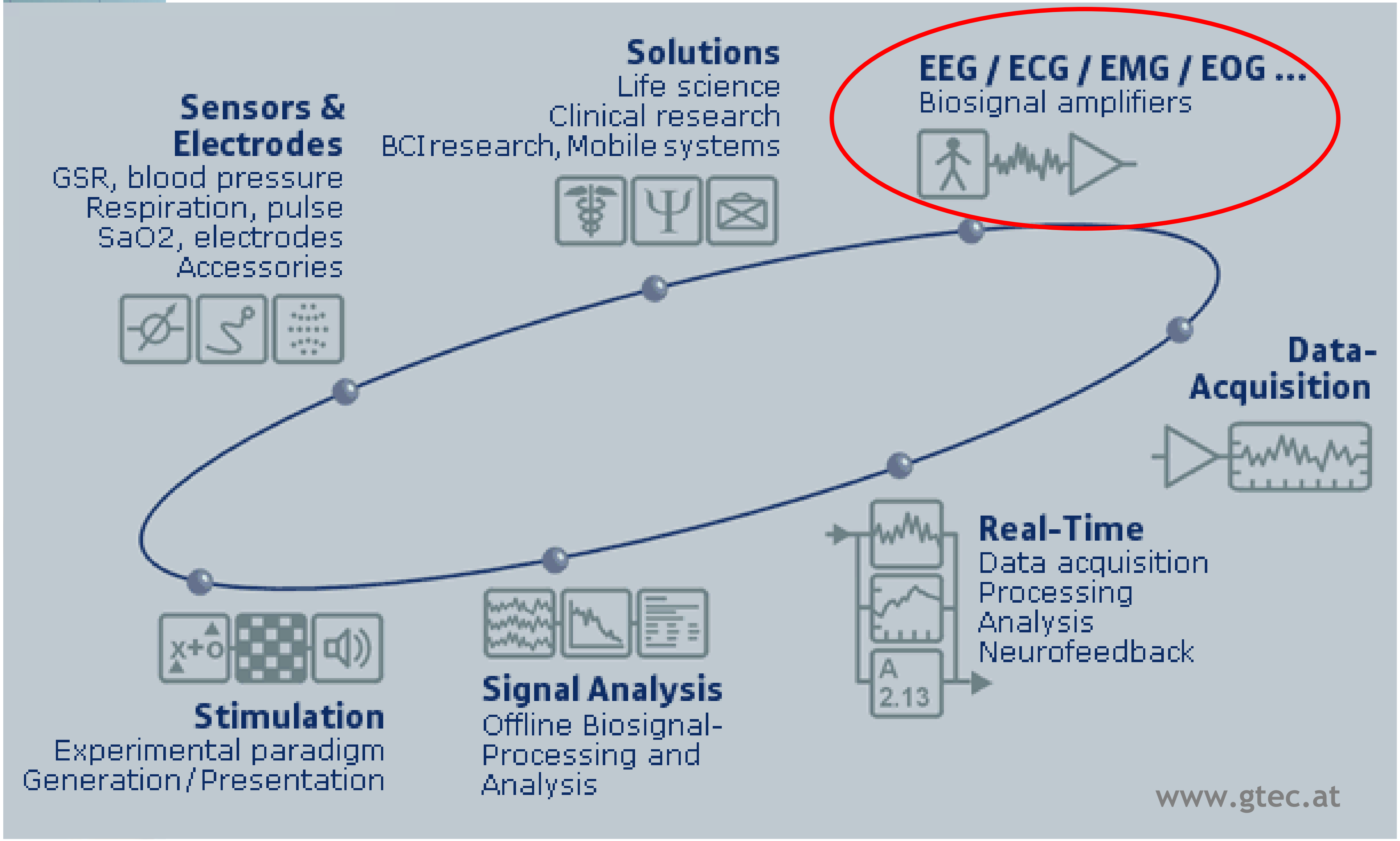

Hardware Development

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EEG, ECoG, EMG, EOG, ECG amplifiers
- 1-128 channels

A. USB based biosignal amplifier
- 16 integrated 24 Bit ADCs
- Floating point DSP
  - re-referencing
  - oversampling (~20000 times)
  - bandpass and notch filtering

B. Mobile device
- 2-4 AA batteries
- 1 integrated 16 Bit ADC
- serial/USB interface
- 1 week operation time
- TCP/IP remote control

C. Stand-alone device
- analog output
- combine it to DAQ board (e.g. NI)
  - resolution
  - sampling frequency
- PCI or PCMCIA board

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Software Programming Environment

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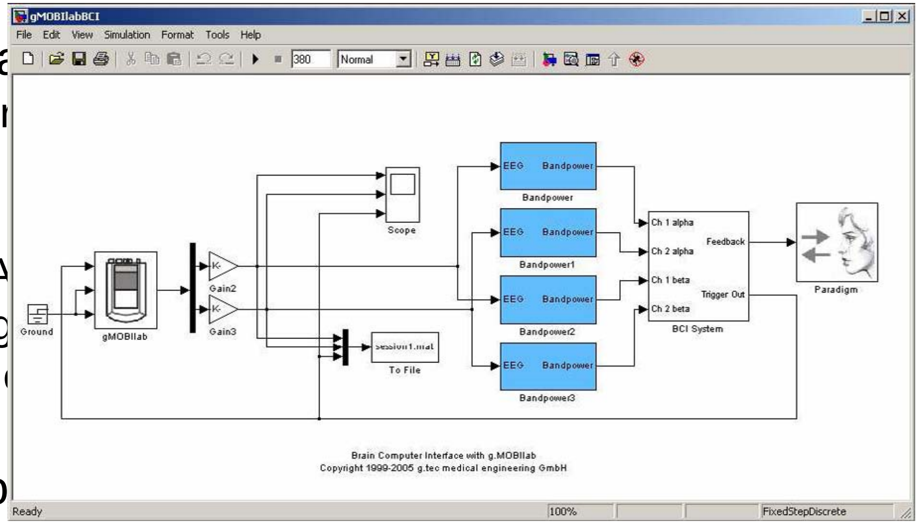
A. C++ Application Program Interfa

- allows to integrate amplifie

B. MATLAB API

- integrate amplifiers into MA
- access to all toolboxes (Sig
- access to user written M-fil



C. Simulink Highspeed on-line Pro

- amplifier device driver block under Simulink
- copy the block into Simulink model and connect the signal processing (S-functions) and paradigm blocks (MATLAB code)
- just exchange the amplifier device driver and work with the same signal processing blocks

All three options give full access to hardware

- bandpass, notch settings
- sampling frequency
- impedance check
- data buffer
- …

Selection of parameter estimation algorithms

(I) Non adaptive estimation:

Band power (optimal frequency bands)

KALCHER et al. 1993

AR parameters

PFURTSCHELLER et al.1997

WOLPAW 1997 ✓

Hjorth parameters

GUGER 1997, OBERMAIER et al. 1999

Common Spatial Patterns (CSP)

MÜLLER - GERKING et al. 1999,

RAMOSER 2000

GUGER 2000

(II) Adaptive estimation

AAR parameters (RLS algorithm)

SCHLÖGL

Selection of classification algorithms

(I) Neural networks (>= 2 classes)

LVQ, DSLVQ

FLOTZINGER et al. 1994
PREGENZER and PFURTSCHELLER 1999

(II) Linear discriminant (2 classes) ✓

signed distance function

PFURTSCHELLER et al. 1998
LUGGER et al. 1998

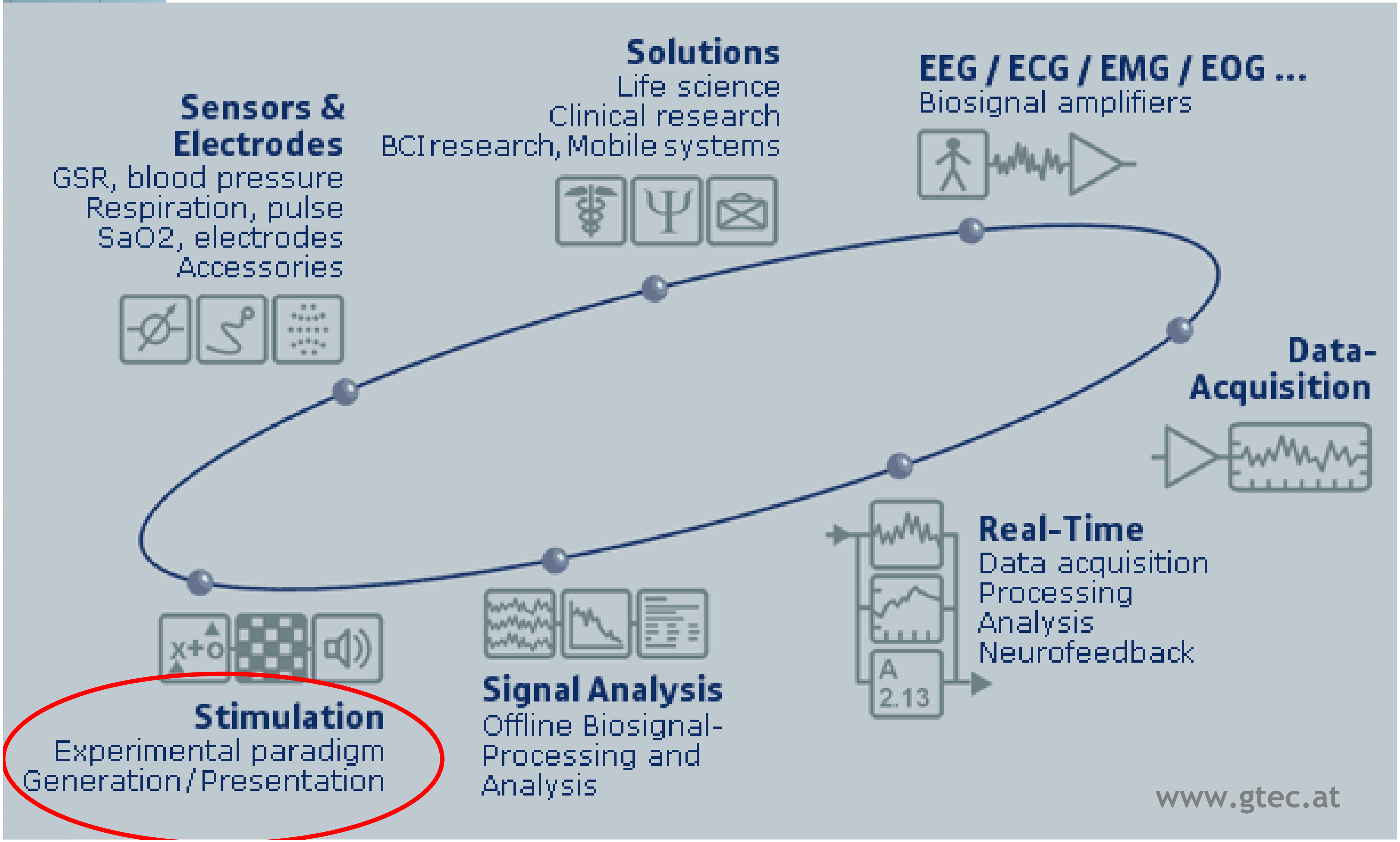
(III) Hidden Markov Models (>=2classes)

OBERMAIER et al. 2001

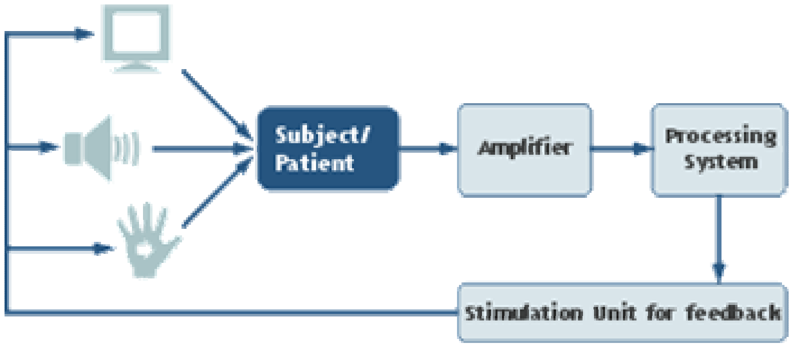
(IV) Support-Vector Machines

MÜLLER

Product range

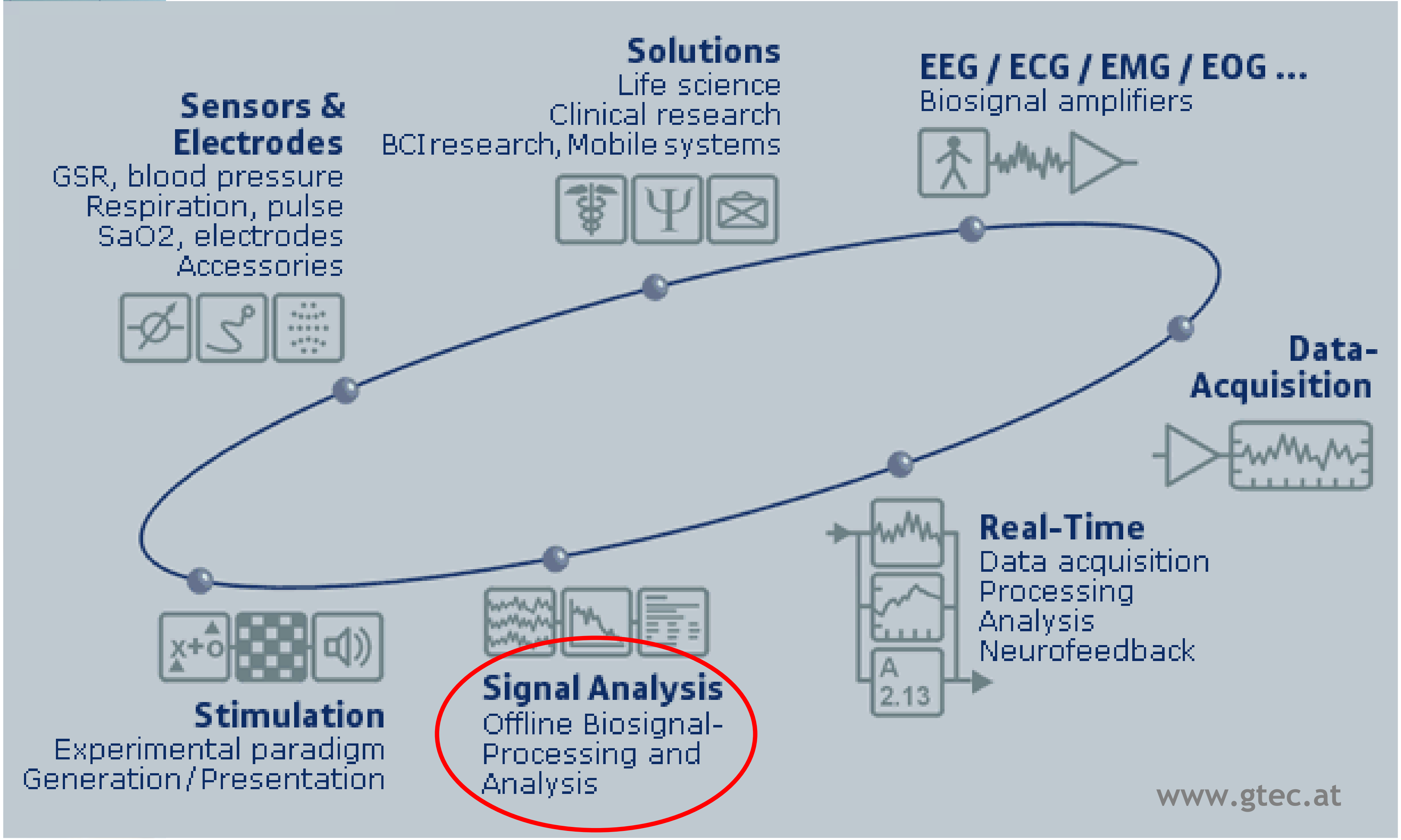


g.*STIMunit* – Stimulation Unit

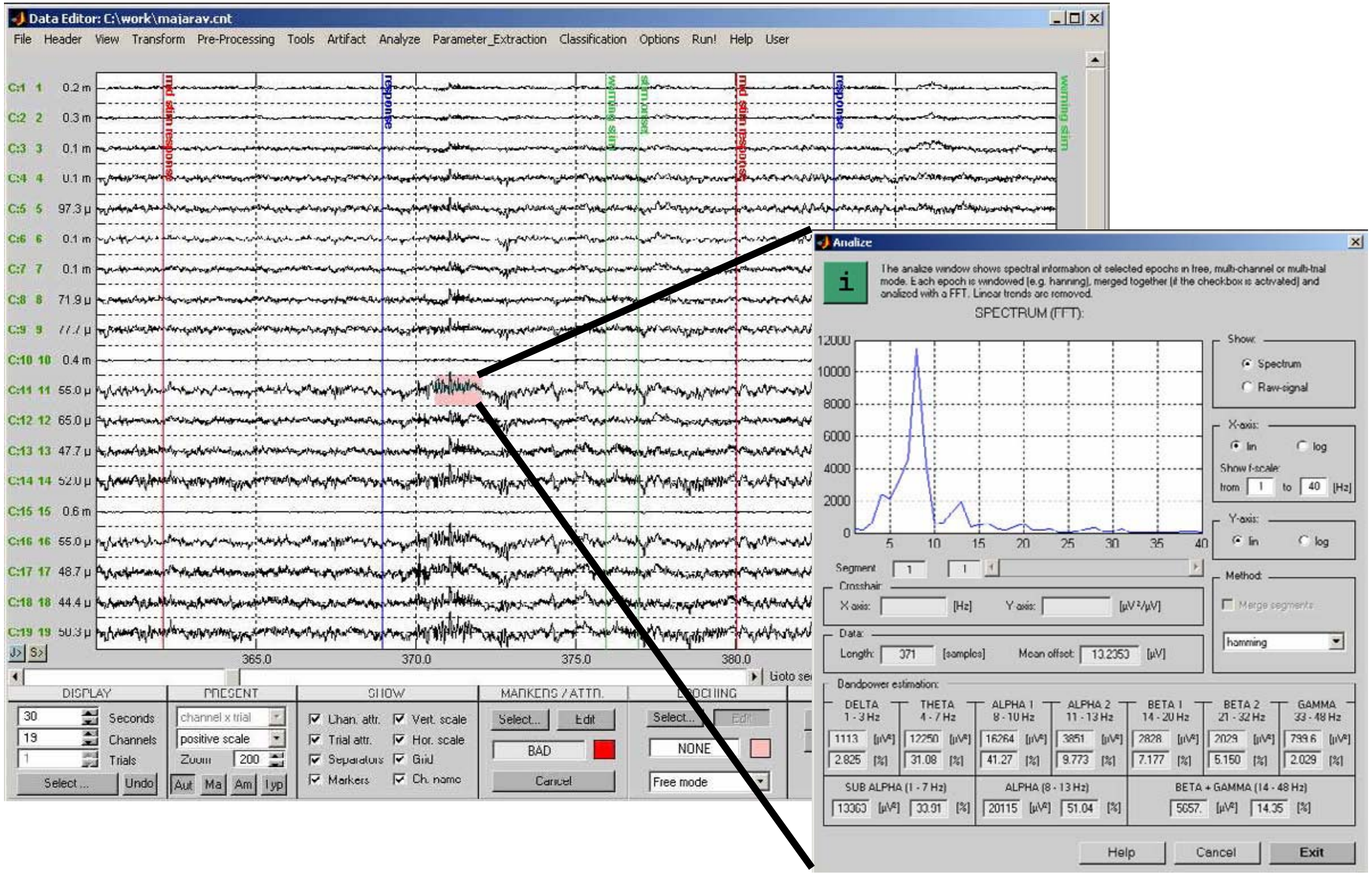


- library for standard neuro- and psycho-physiological paradigms
- accurate timing for visual, auditory and tactile stimulation
- MATLAB based paradigm parser for easy development of user-specific experiments
- logging of subject responses and real-time biofeedback to the subject/patient
- create easily test batteries for cognitive tasks (human intelligence and neural efficiency) and motor tasks (rehabilitation for stroke, epilepsy, Parkinson's disease)
- simulate traffic flow or flight control scenes to investigate the workload of pilots

Product range



g.BSanalyze – Offline Processing Software



Requirements for high quality EEG recordings and BCI applications

- The lab: shielding, light, monitor position, chair, silence

- Technical aspects: amplifier placement, electrode leads, type of electrode/cap, impedance, ...

- The artifact problem: amplifier, electrodes, physiological artifacts, systematic artifacts

- Instruction of the subject: fixation cross, muscle relax, eye-blinks, duration of runs, breaks, motivation

How can the computer read your thoughts?

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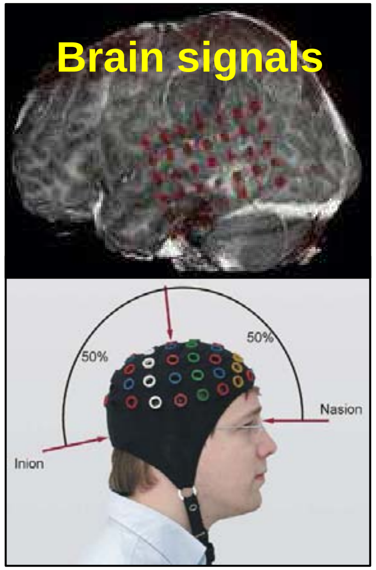


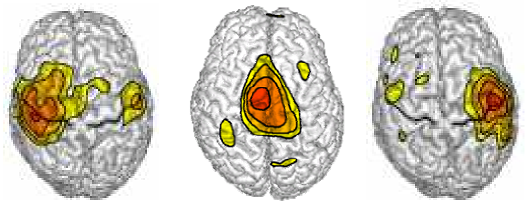
Produce unique brain activity patterns

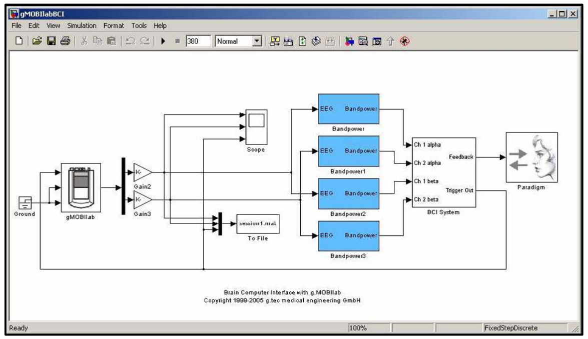
Think about a hand/foot movements

Concentrate on an event - flashing letter

High-end and robust brain signal amplifier

Signal processing & Pattern recognition





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Changes of brain electrical activity and mental strategies

- Slow cortical potentials (anticipation tasks)
  DC-derivation, artifact problem, difficult strategy, feedback method

- Steady state evoked potentials (focus of attention task)
  Thalamic gating, various methods of stimulation (visual, tactile, electrical, auditory, ...)

- Phase-locked potentials, readiness potentials, motor potentials (motor tasks)
  Template matching, spatial distribution, large number of electrodes, ECoG electrode grid

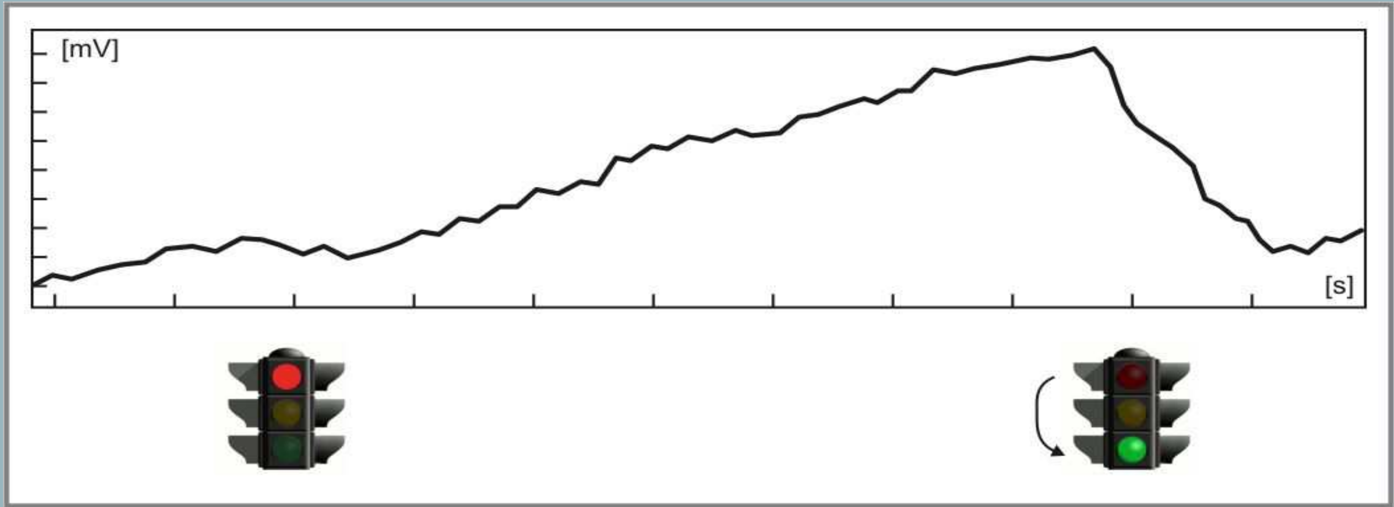
- Event-related, non-phase-locked changes of oscillatory activity ERD/ERS (motor imagery tasks)
  Changes of mu-rhythm, alpha activity and beta activity over sensorimotor areas,
  Imageries of hand- ,foot-, tongue- movements

Communication for the ´locked-in´

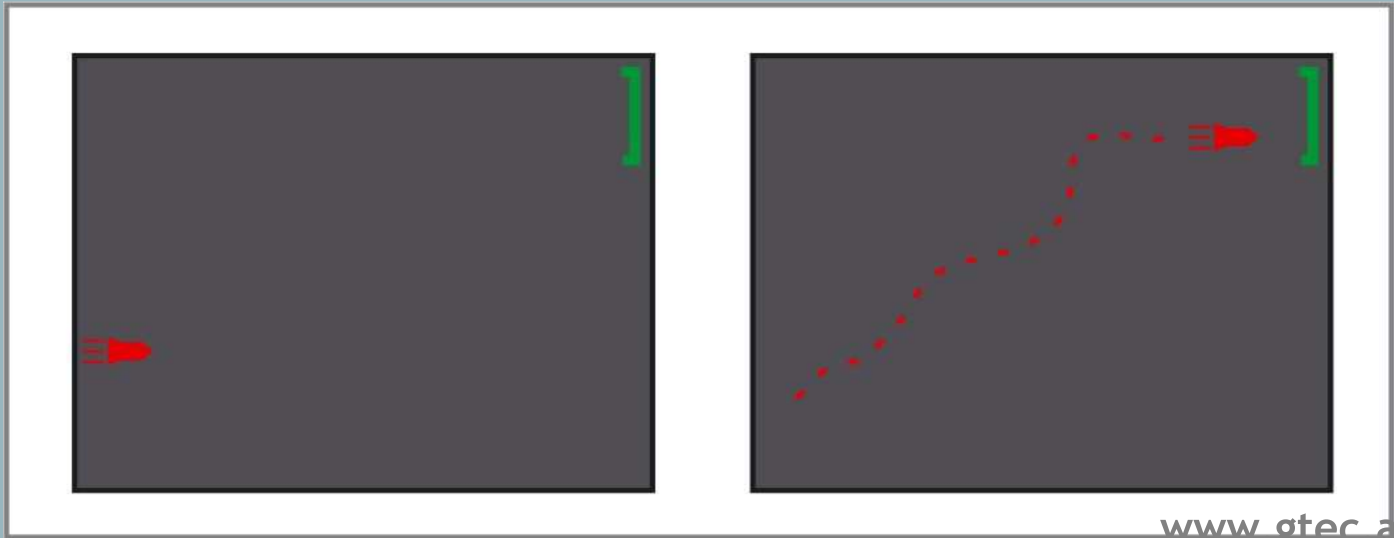
ALS patient in Germany using a BCI system for communication
Birbaumer, Kübler, Hinterberger,… Tübingen

Slow Cortical Potentials

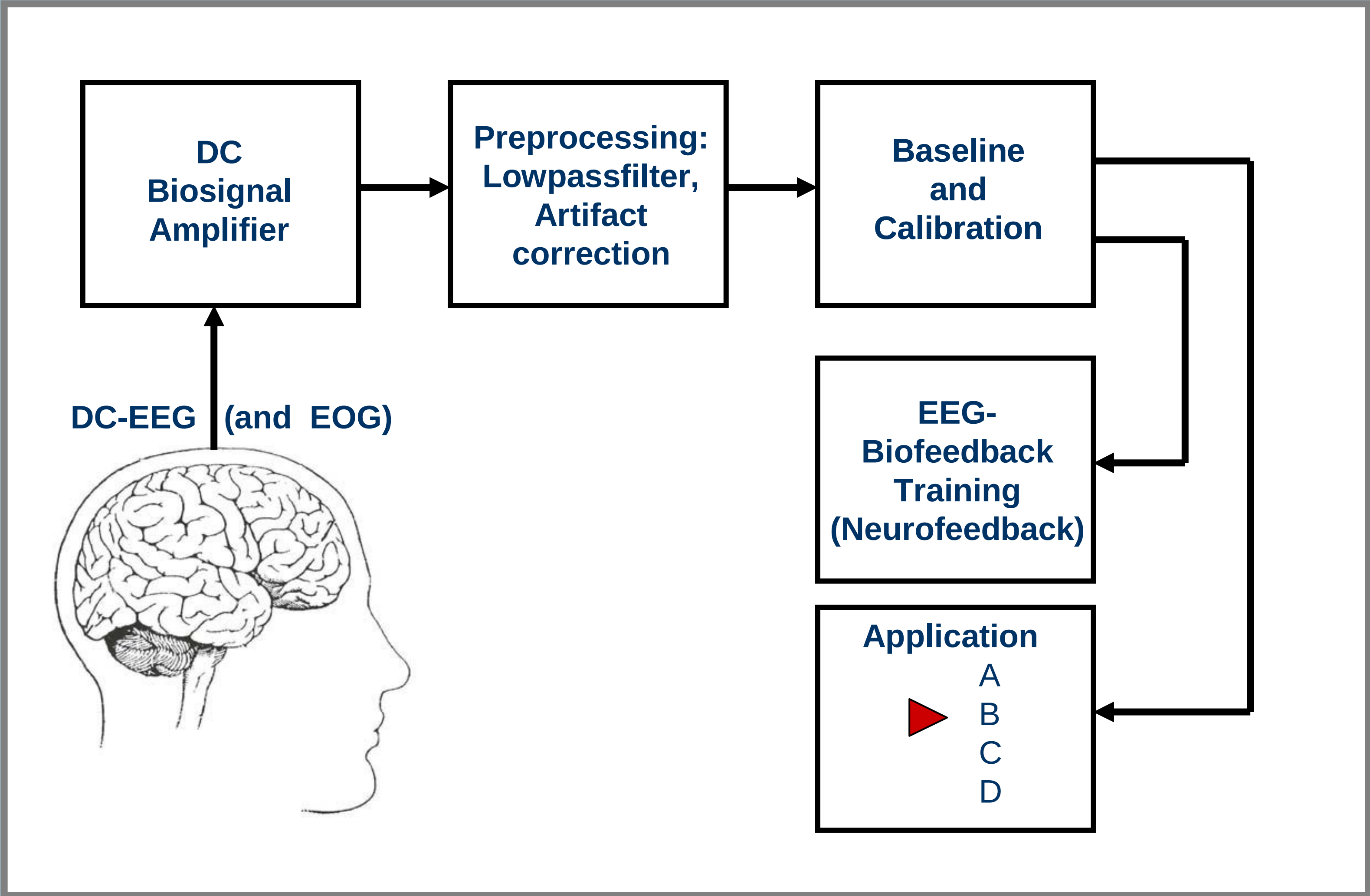
MENTAL
TASK



BIOFEEDBACK
TRAINING



Slow Cortical Potentials



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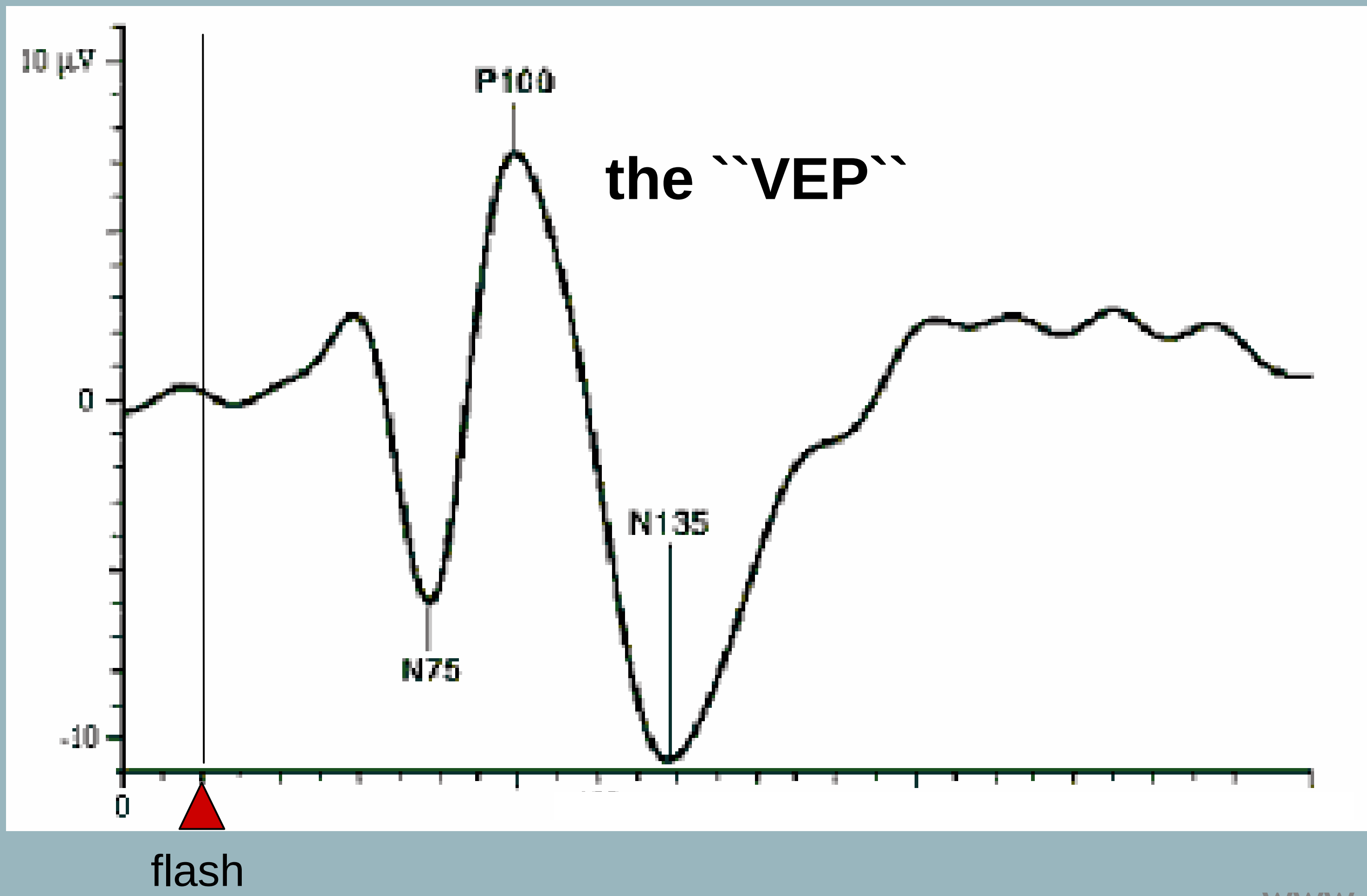
Steady-State Visual Evoked Potentials (SSVEP)



Steady-State Visual Evoked Potentials (SSVEP)

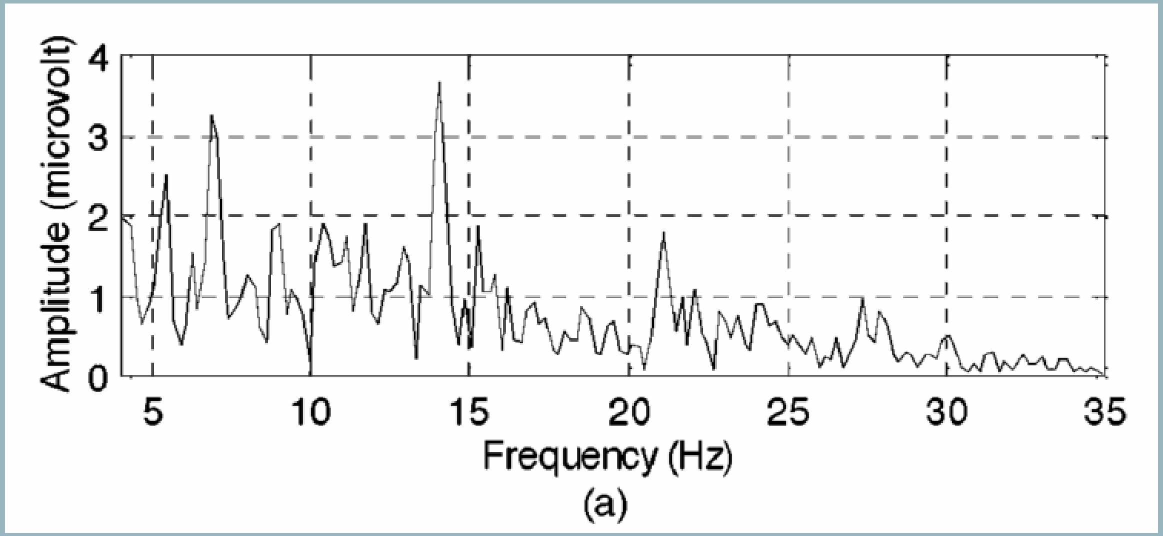
Frequency of stimulation	Brain response
0 ... 2 Hz	transient (single) VEP
3 ... 5 Hz	undefined response
6 ... 24 Hz	SSVEP

Steady-State Visual Evoked Potentials (SSVEP)

7 Hz

Steady-State Visual Evoked Potentials

7 Hz



Steady-State Visual Evoked Potentials (SSVEP)

Steady-State Visual Evoked Potentials

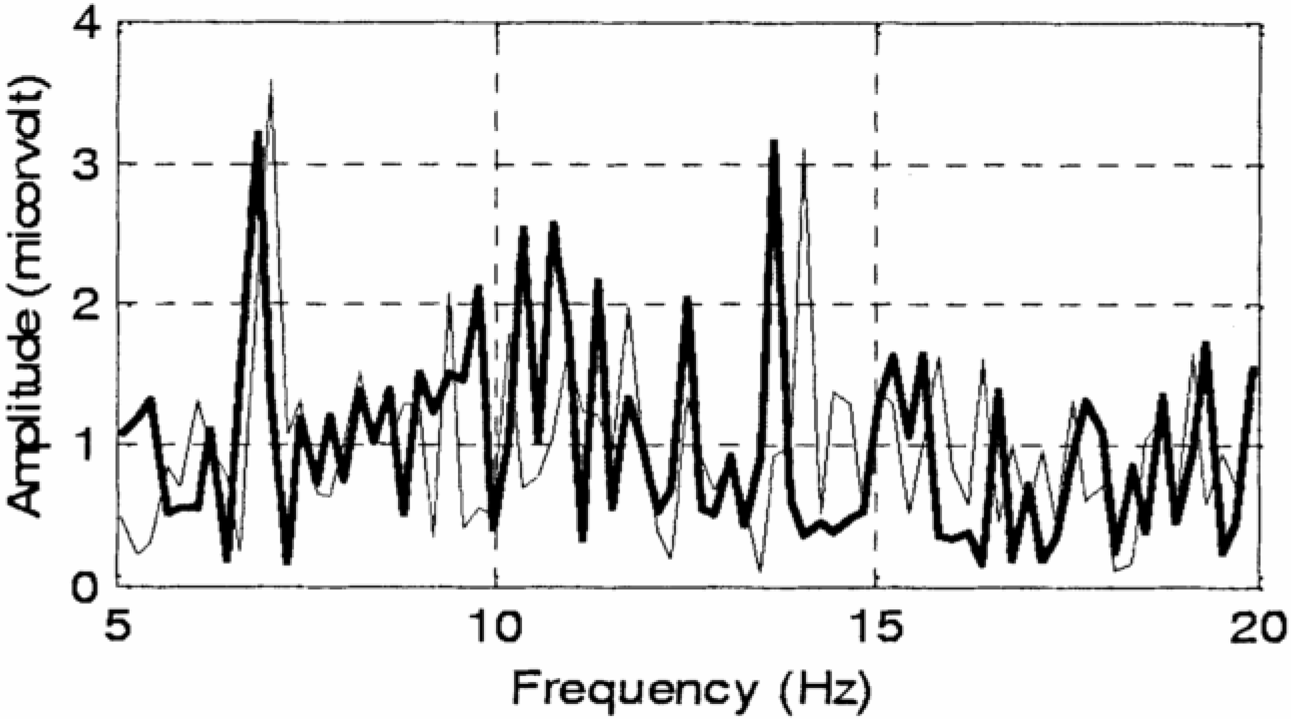
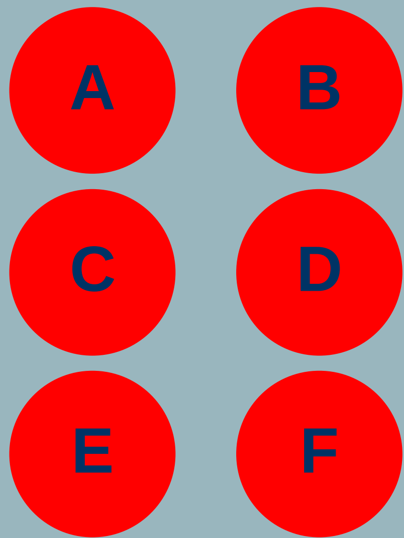


Fig. 1. Amplitude spectra of SSVEPs induced by 6.83- (thick) and 7.03-Hz (thin) visual stimulation.

Steady-State Visual Evoked Potentials (SSVEP)



up to 48 different frequencies possible!

ERD/ERS BCI

Changes of brain electrical activity and mental strategies

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  Imageries of hand- ,foot-, tongue- movements

The ``Motor Imagery Task``

Event-related desynchronization (ERD) and sychronization (ERS) over sensory-motor areas occur for ...

... planning of movements

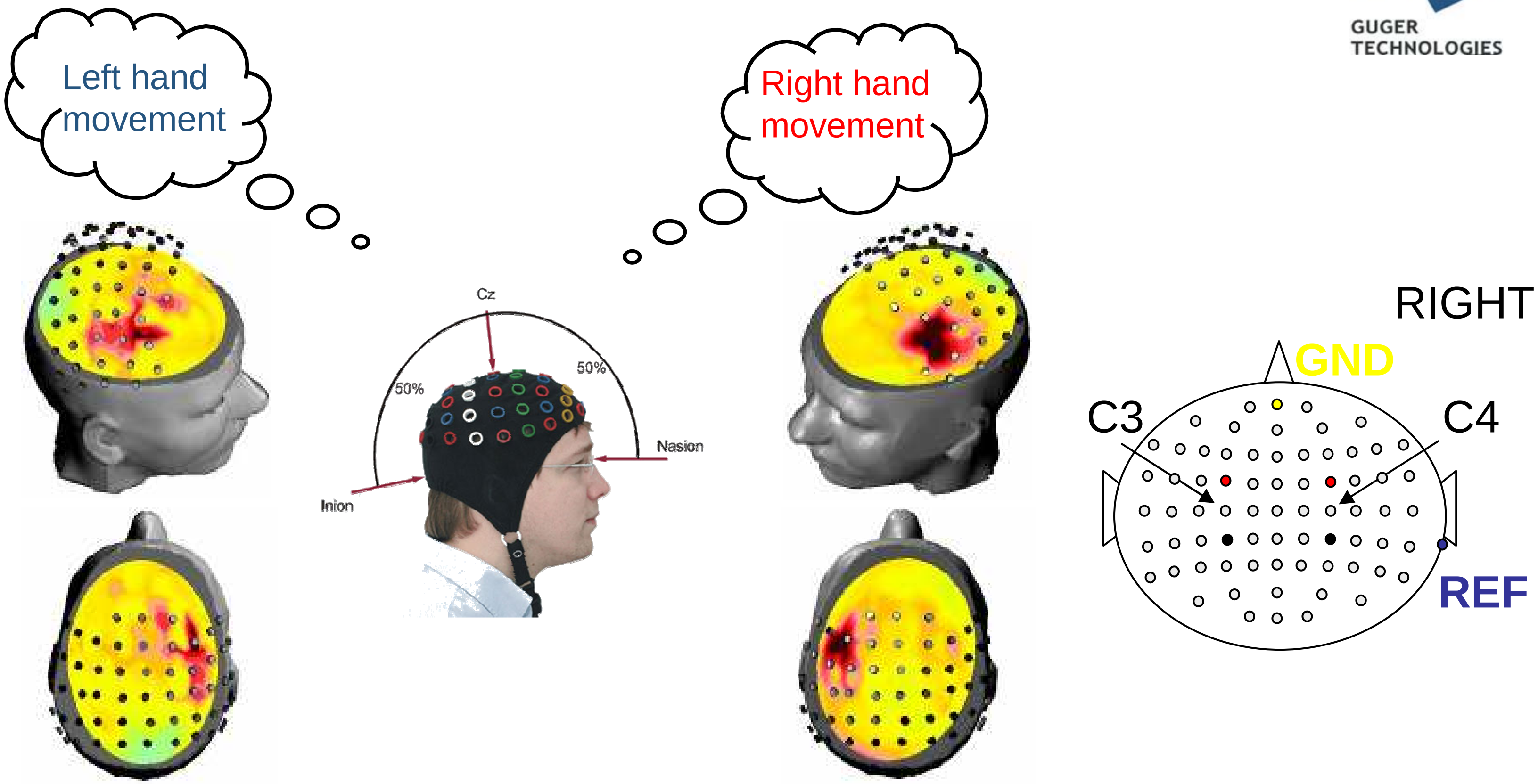
... execution of movements

... imagination of movements

... passive movements

(... observation of movements)

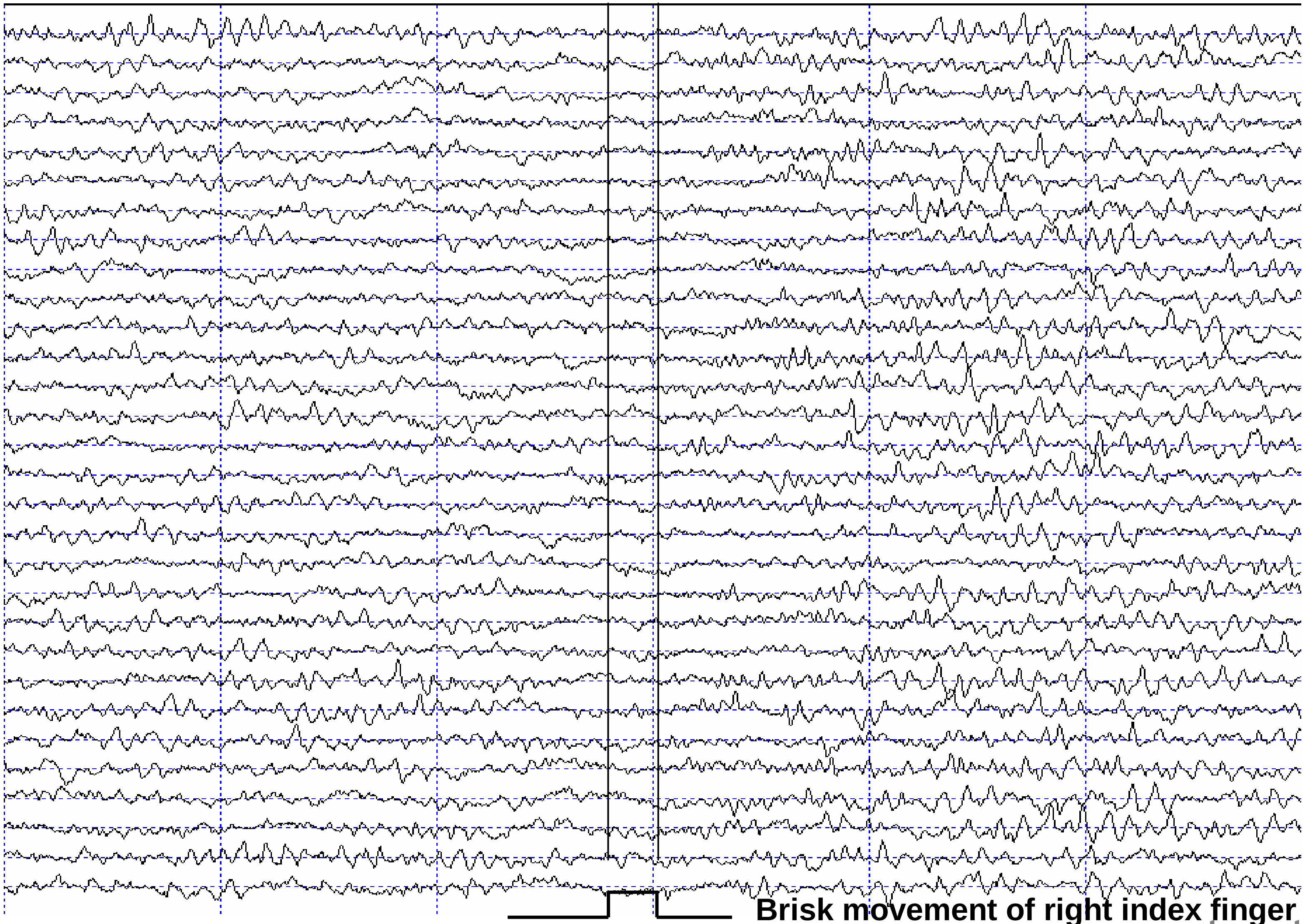
Physiological Background – why does it work



Imagination of hand movement causes an ERD which is used to classify the side of movement. The desynchronization occurs in motor and related areas of the brain. Therefore, for analyzing and classifying ERD-patterns the electrodes must be placed close to sensorimotor areas.

C3

The ``Finger Movement Task``



Brisk movement of right index finger

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Oscillatory EEG Activity (example)

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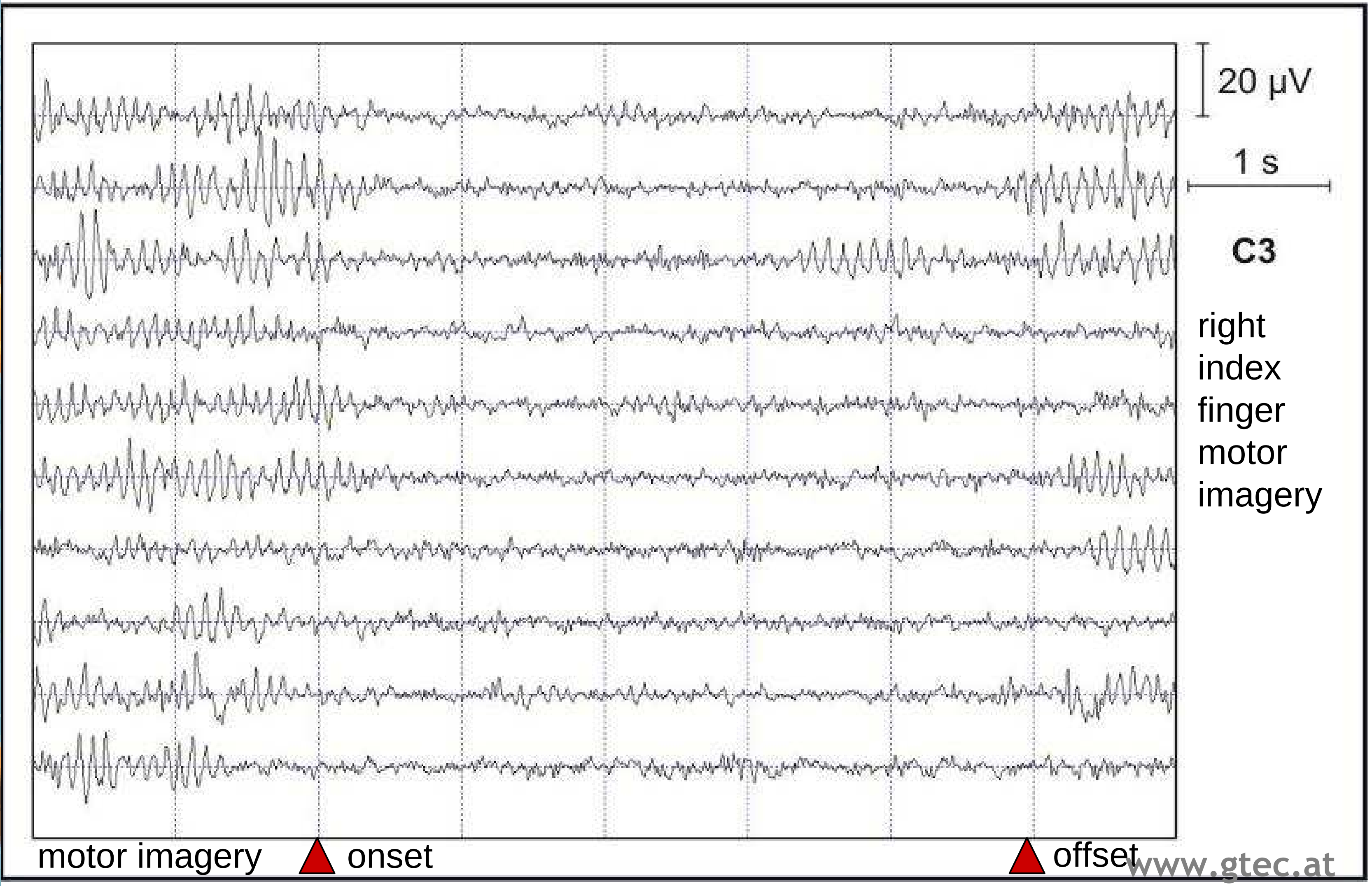
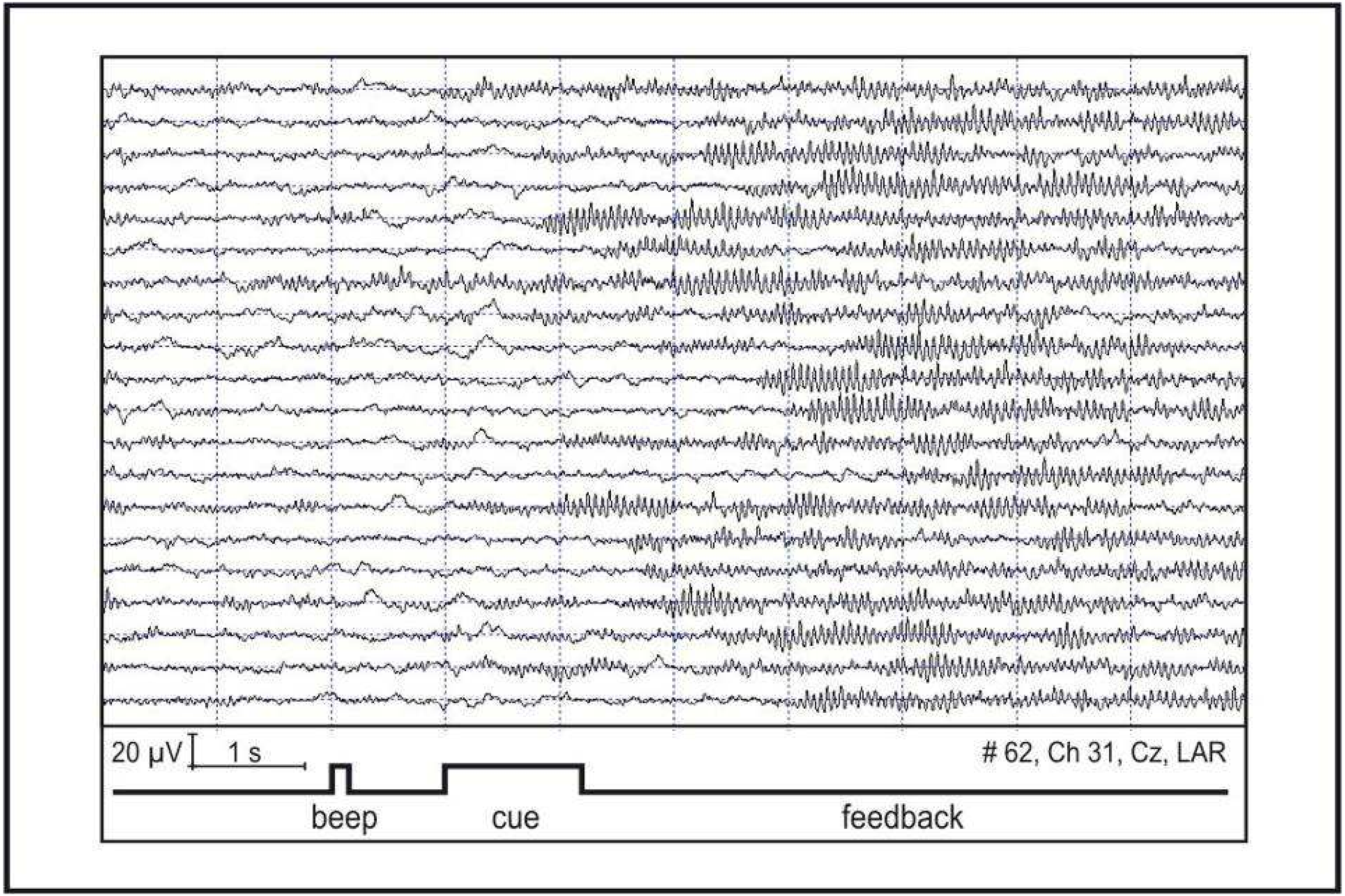
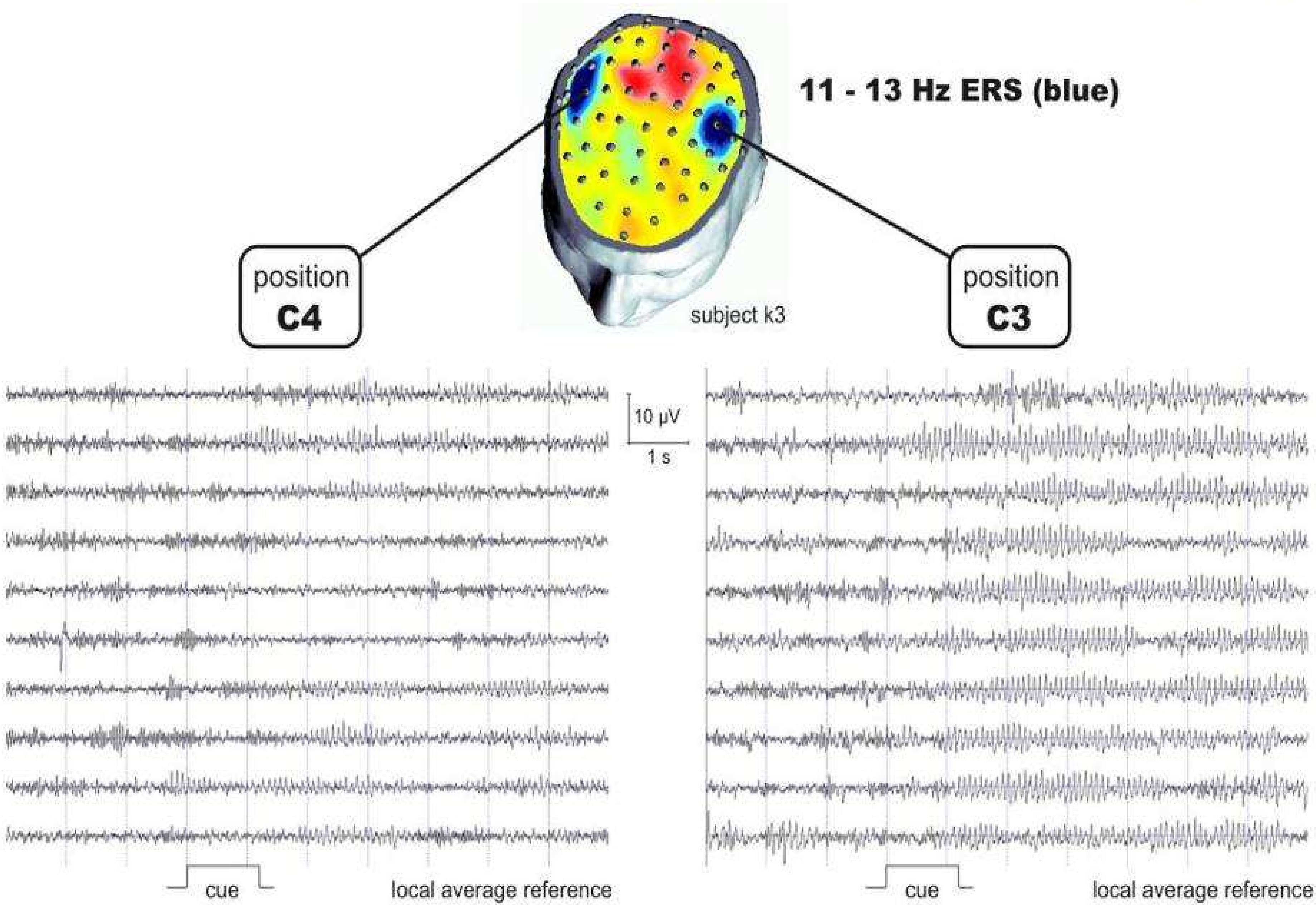


Oscillatory EEG Activity (example)



Hand-area mu-ERS during foot motor imagery



Which type of “thought” should be used?

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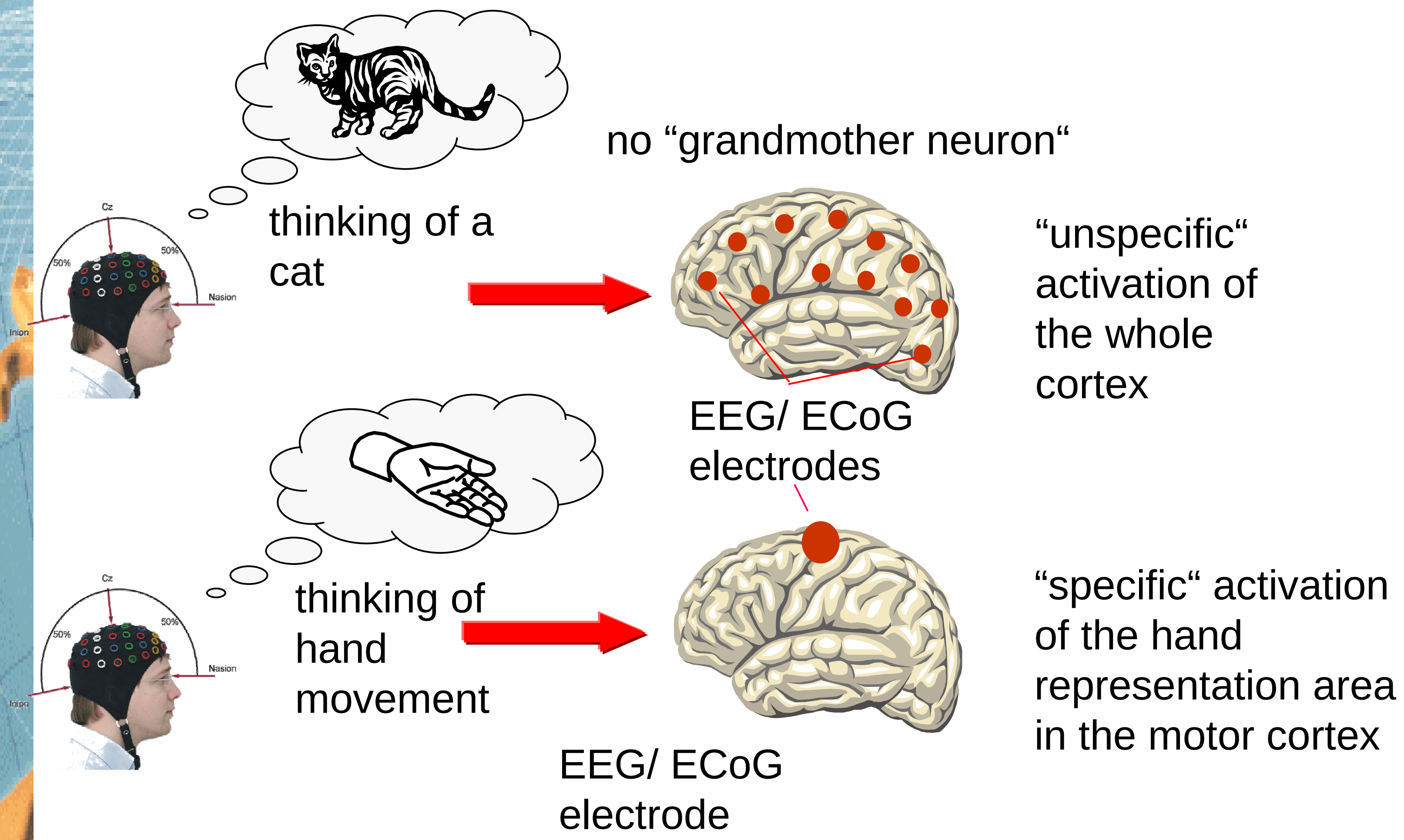
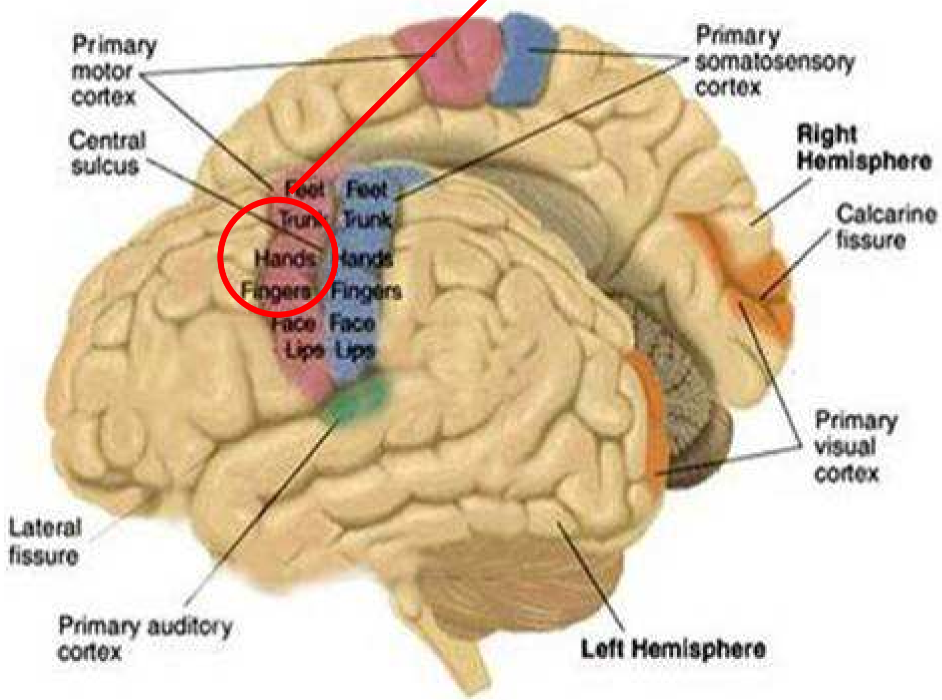
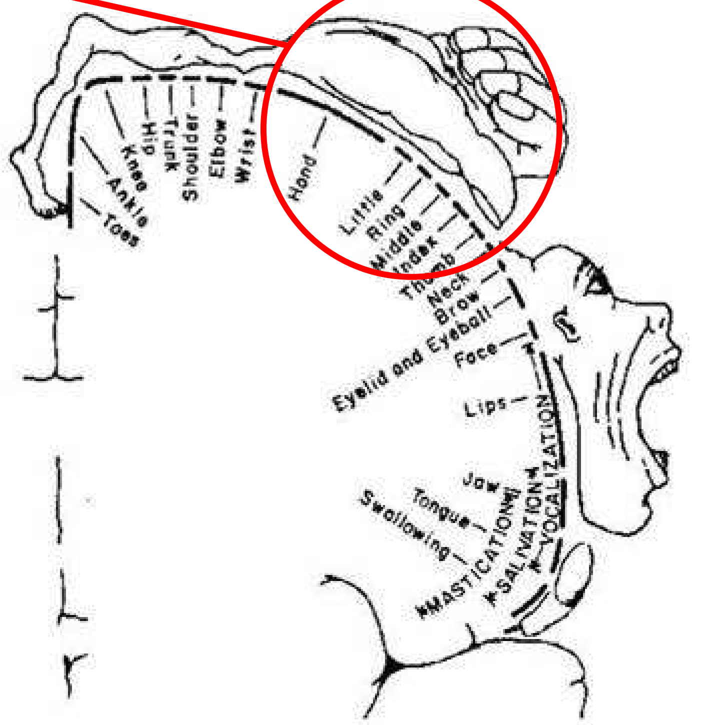


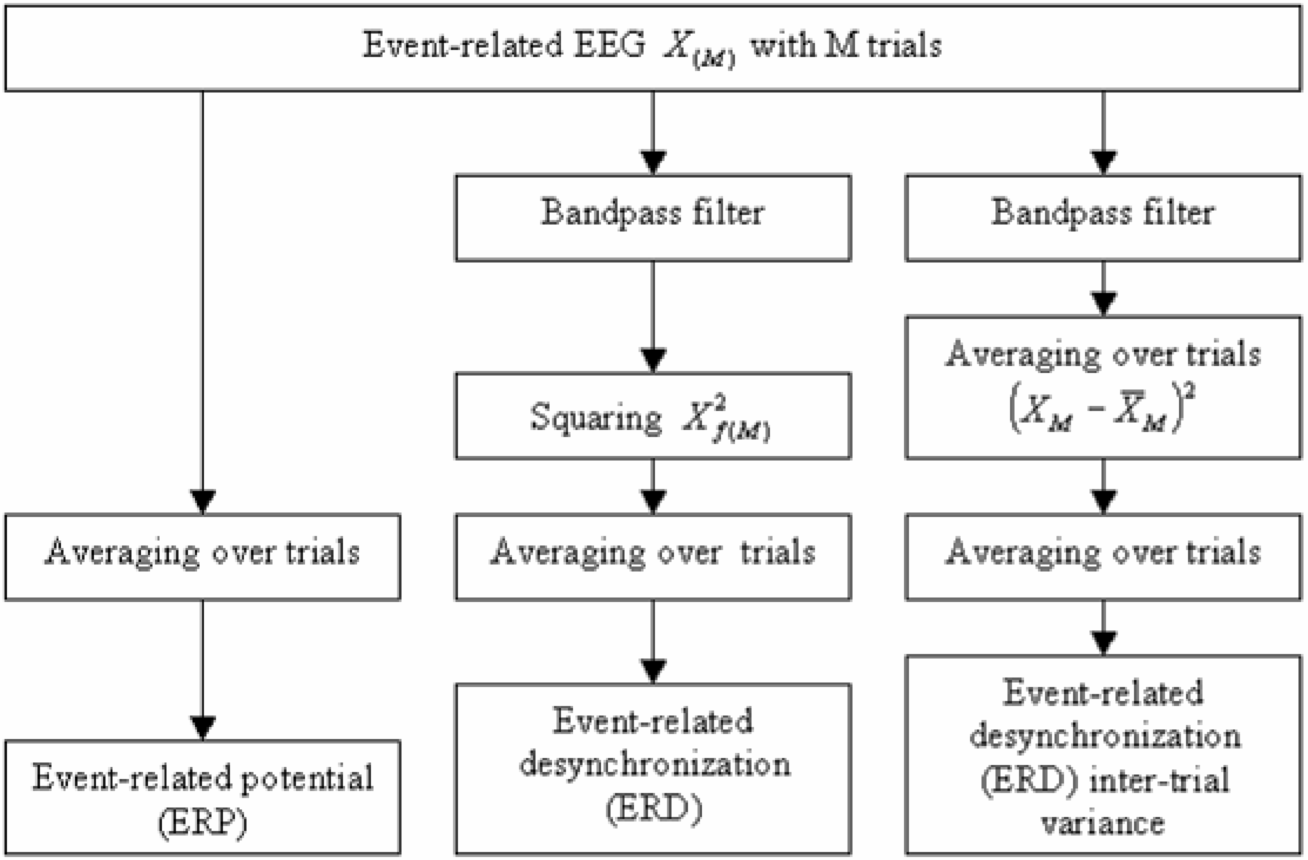
Somatotopic organisation of the motor cortex

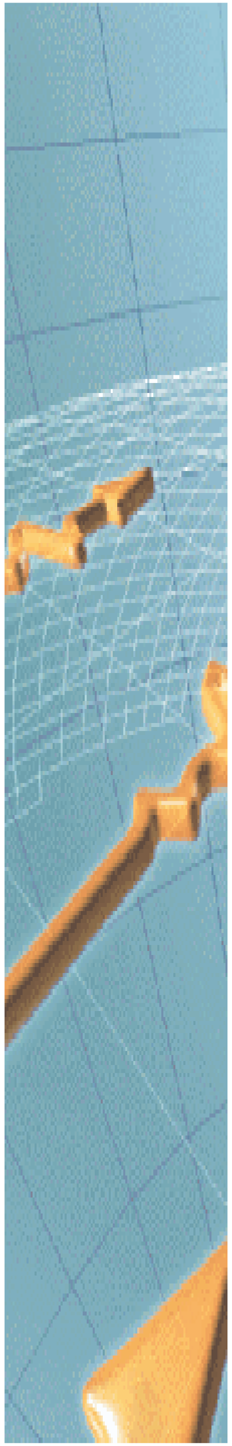
Hand representation area





Event-related-desynchronisation/synchronization





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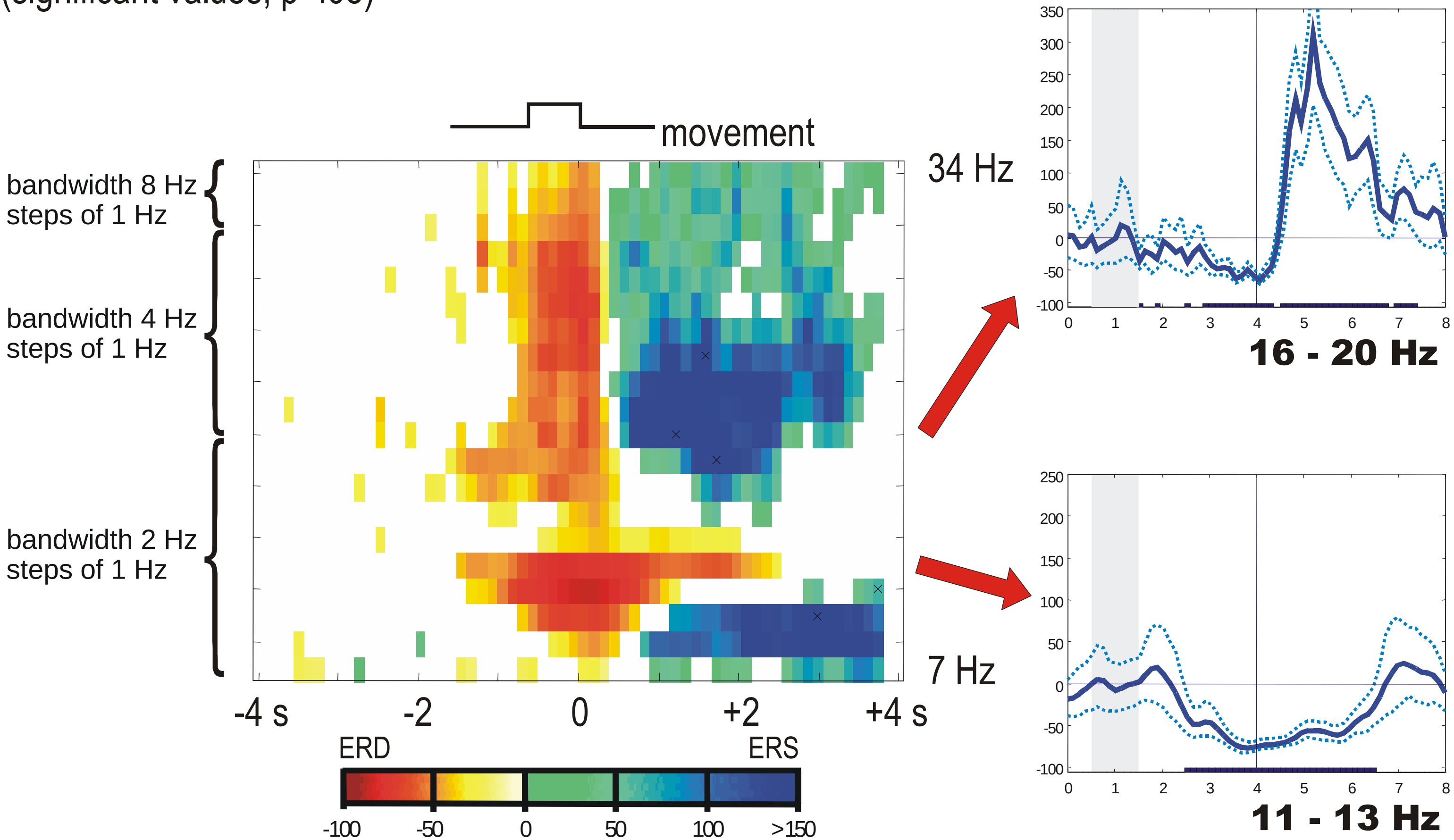
Time- frequency mapping of ERD / ERS

ERD/ERS map for electrode C3, right index finger movement

(significant values, p<.05)



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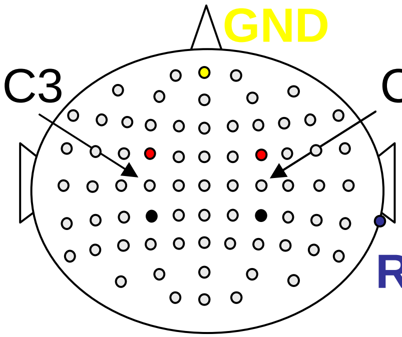
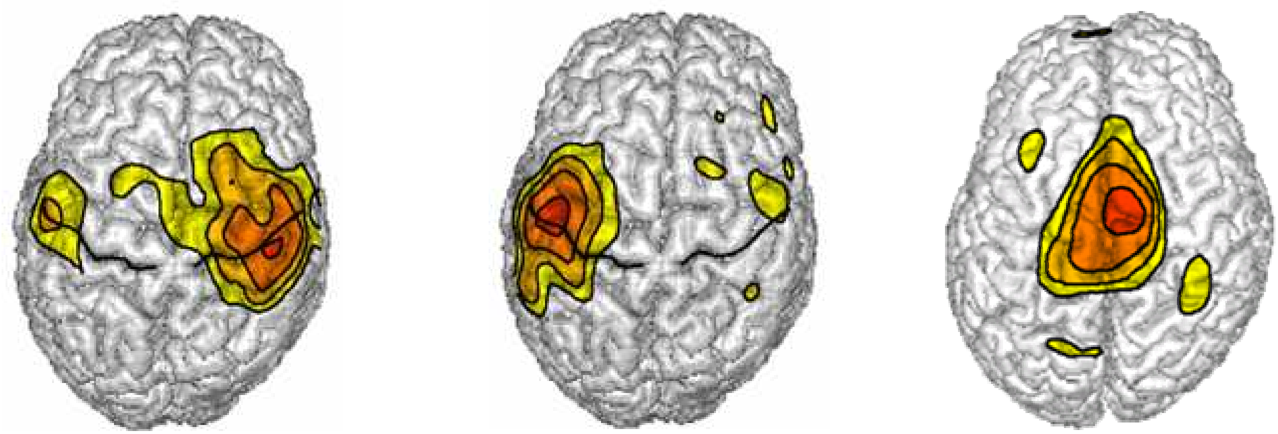
Mental strategies





Left hand

Right hand

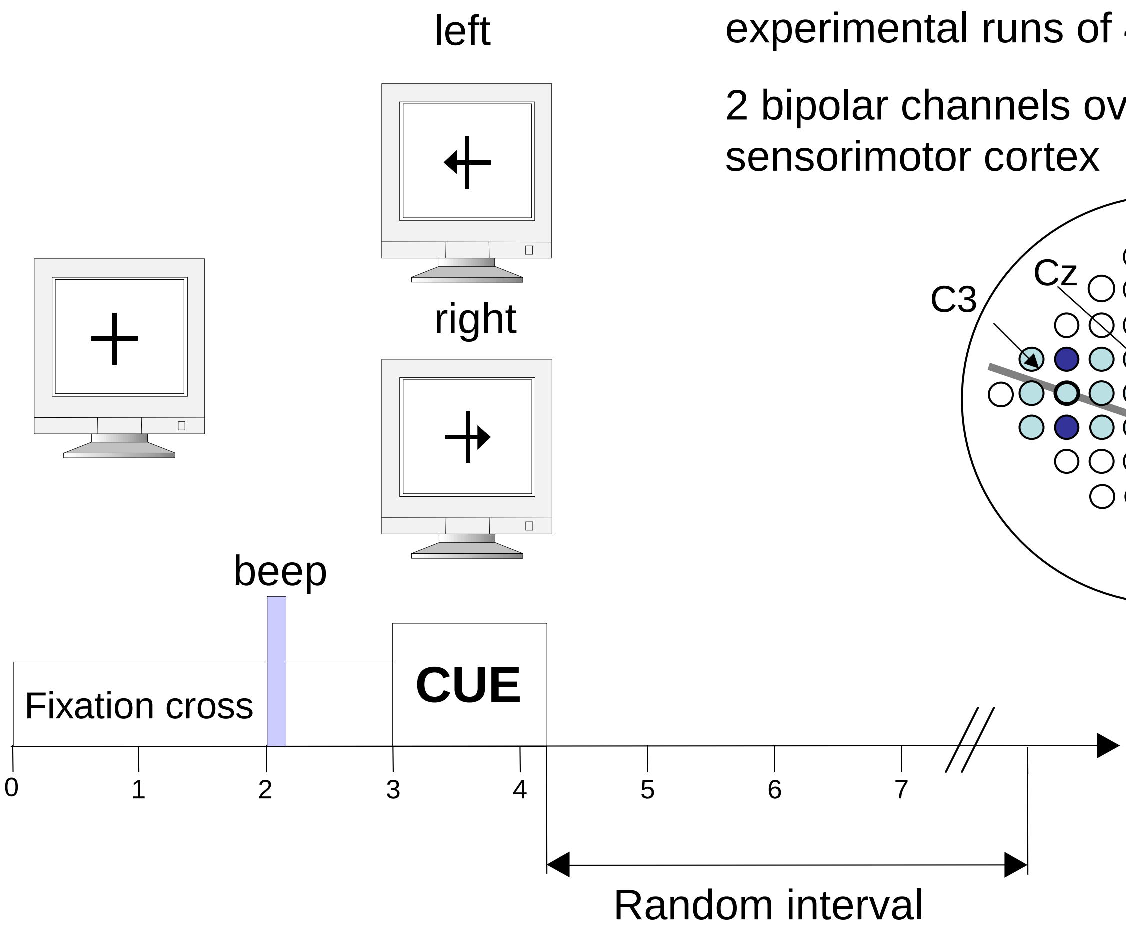
motor imagery

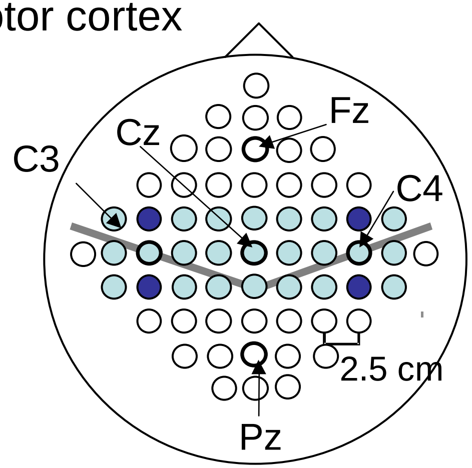
Foot

Off-line simulation - Paradigm

Each session was divided into 4 experimental runs of 40 trials

2 bipolar channels over sensorimotor cortex





Training BCI Control

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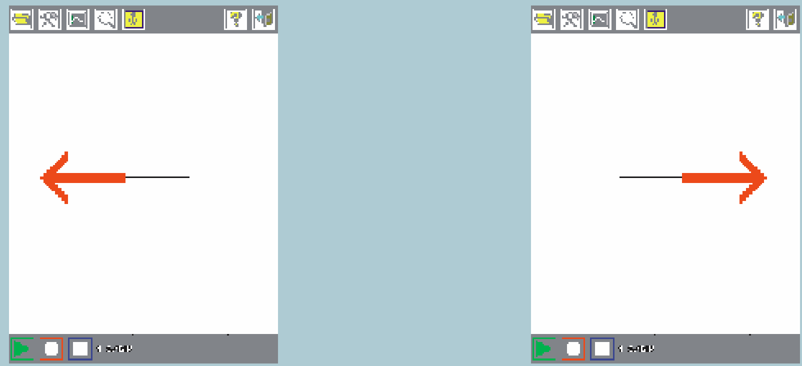
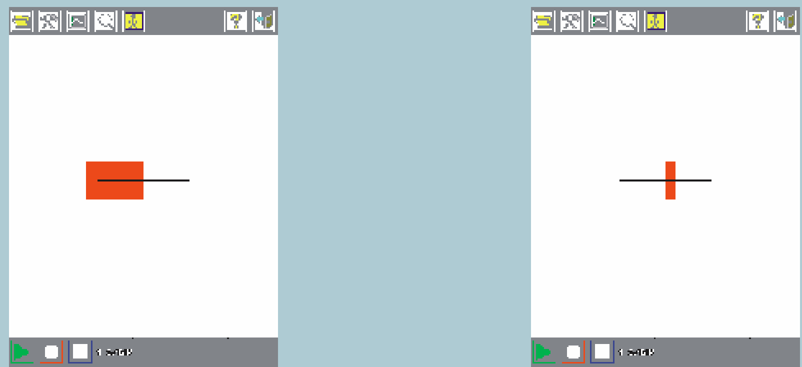
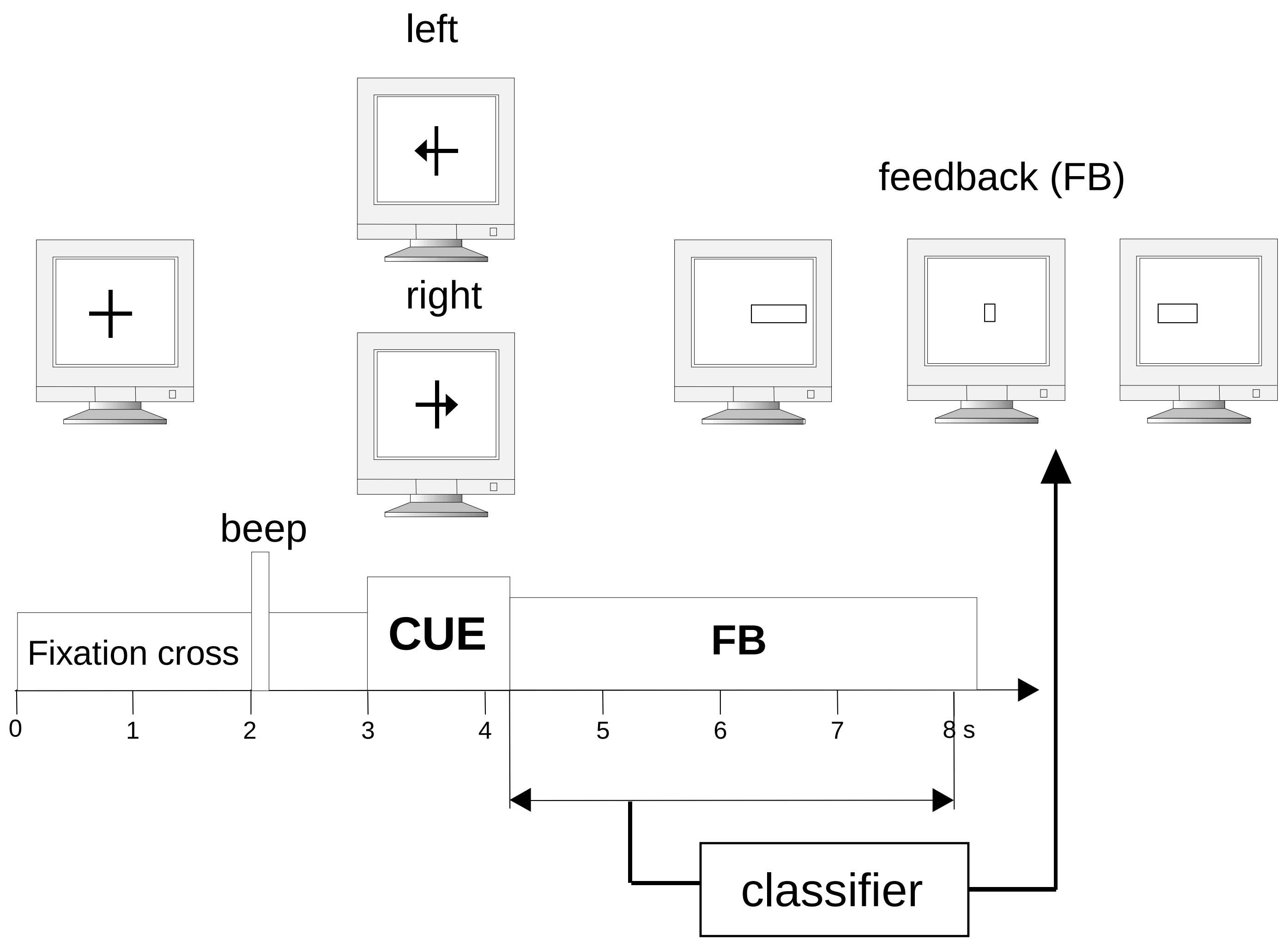
Training phase



Feedback / BCI application phase

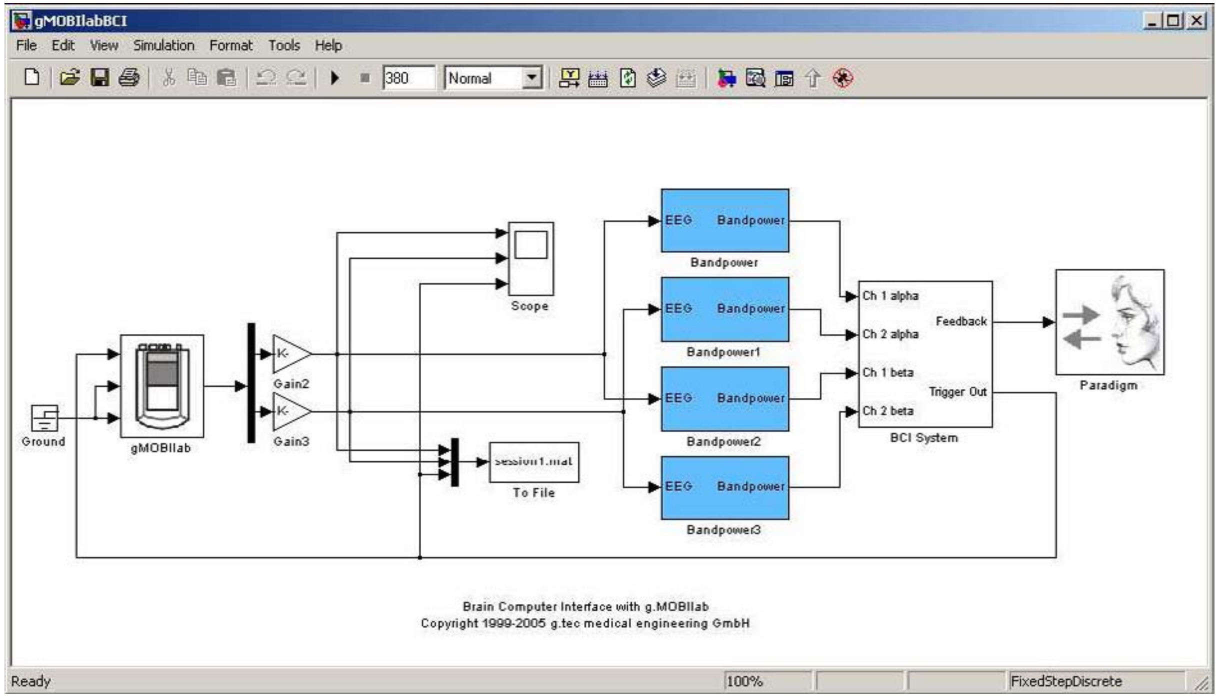


Connection to real world – Imagination with continuous feedback

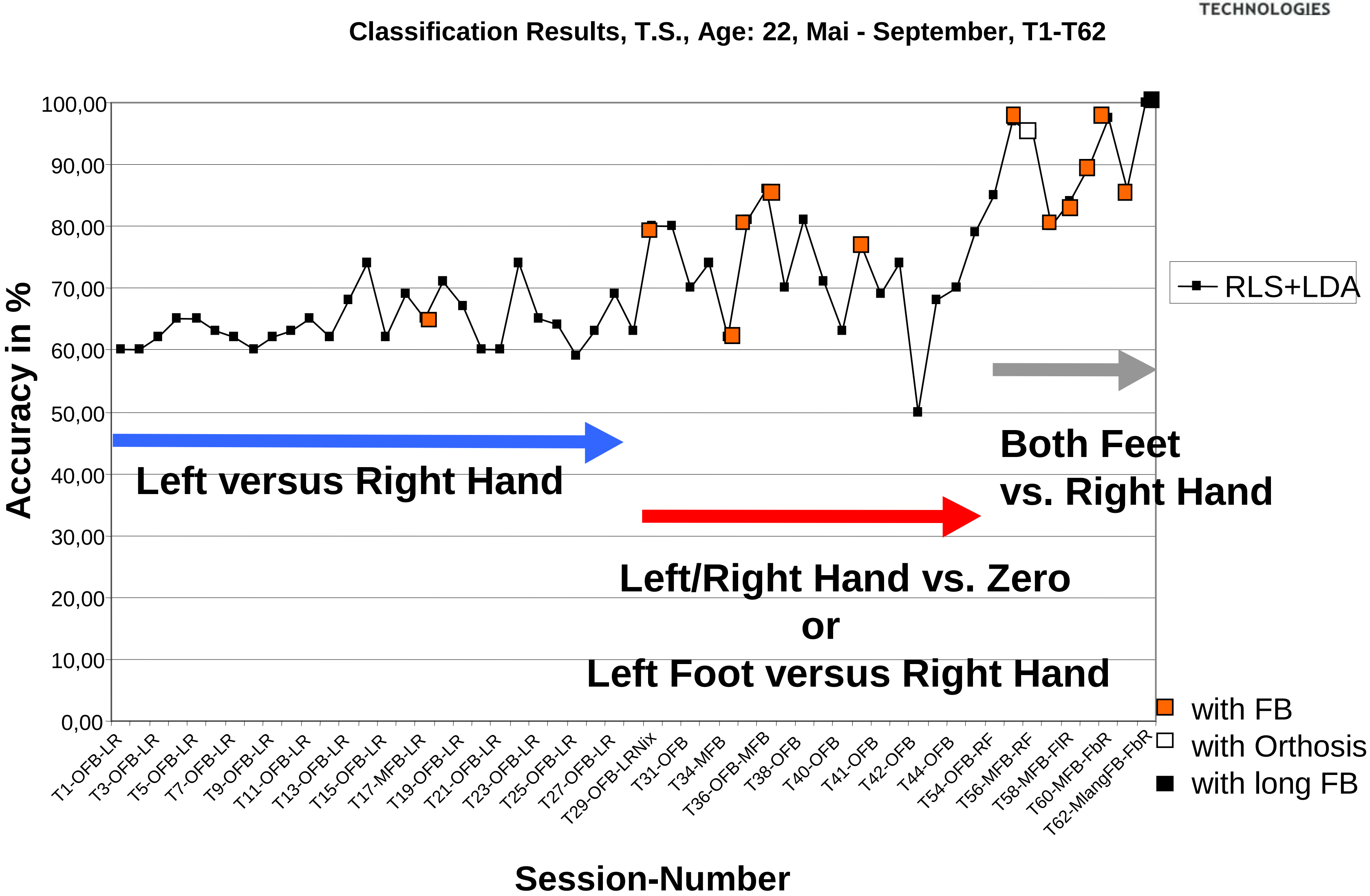


g.USBamp Simulink Highspeed on-line Processing

- amplifier device driver block reads data into Simulink in real-time
- blocks for signal visualization and data storage
- feature extraction with bandpower algorithm implemented as S-function in C
- on-line linear discriminant analysis
- paradigm implemented as S-function with MATLAB code



Training Results




Brain Interface (AT)
Move through virtual environments by thoughts
Products:
EU

How many people can control a BCI?

- BCI system at exhibition about bio-technology in Graz

 (6 months duration)

- data of all 99 subjects (first 2 month)
- 1 run without feedback
- next run with feedback
- 2 bipolar derivations analyzed with adaptive autoregressive parameters or bandpower of predefined frequency bands

Classification Accuracy in %	RLS Percentage of Runs (N=76)	BP Percentage of Runs (N=117)	RLS+BP Percentage of Runs (N=193)
90-100	6.6	6.0	6.2
80-89	10.5	14.5	13.0
70-79	30.3	33.3	32.1
60-69	40.8	42.7	42.0
50-59	11.8	3.4	6.7
	100	100	100

Position reconstruction with place cells

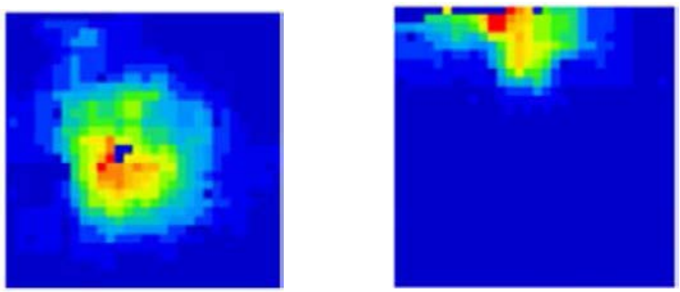
Place cells are located in the hippocampus

Place cells fire only at specific positions

The action potentials are measured with tetrodes inserted into the animal brain

Recordings performed with rats

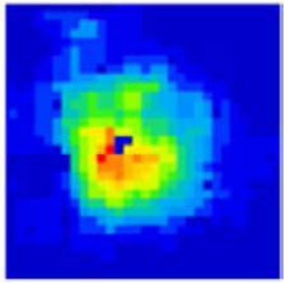
cell 1 **cell 2**



The Rat-GPS

Spikes

Rat

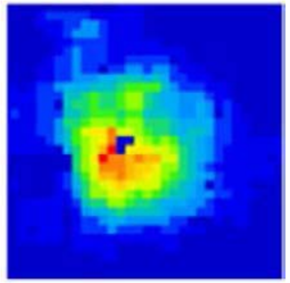


Camera

Encoding Step

Spikes

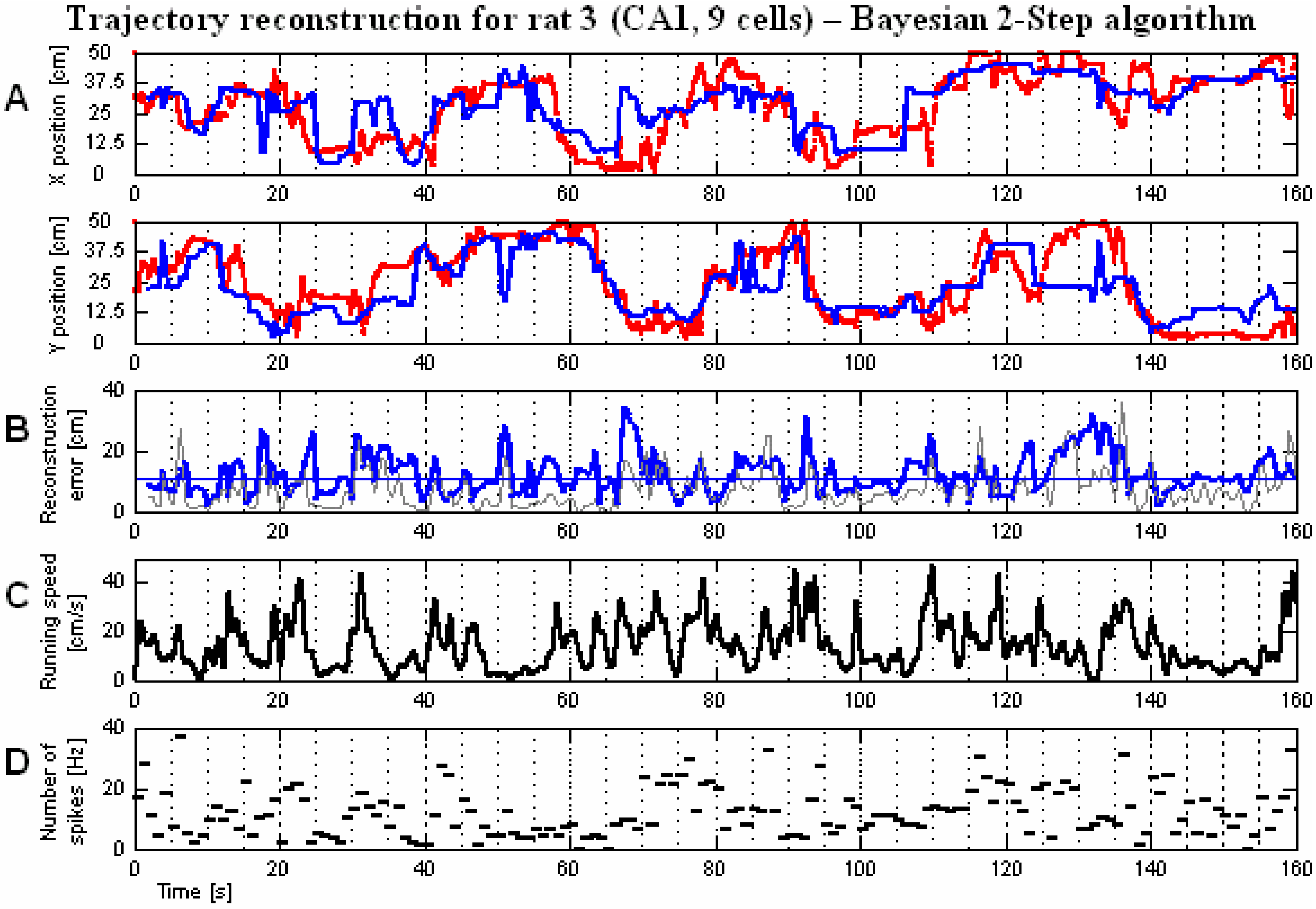
Rat



Predict Position

Decoding Step

Accuracy of position recognition



We are already able to do this on-line !

Live Experiment:
I) P300 based speller

Changes of brain electrical activity and mental strategies

- Slow cortical potentials (anticipation tasks)
  DC-derivation, artifact problem, difficult strategy, feedback method

- **Evoked potentials (focus of attention task)**
  Thalamic gating, various methods of stimulation (visual, tactile, electrical, auditory, ...), P300

- Phase-locked potentials, readiness potentials, motor potentials (motor tasks)
  Template matching, spatial distribution, large number of electrodes, ECoG electrode grid

- Event-related, non-phase-locked changes of oscillatory activity ERD/ERS (motor imagery tasks)
  Changes of mu-rhythm, alpha activity and beta activity over sensorimotor areas
  Imageries of hand- ,foot-, tongue- movements

Physiological background

- **P300 - Evoked Response Potential (ERP)**

  - is obtained from EEG’s (spontaneous brain activity) by averaging techniques

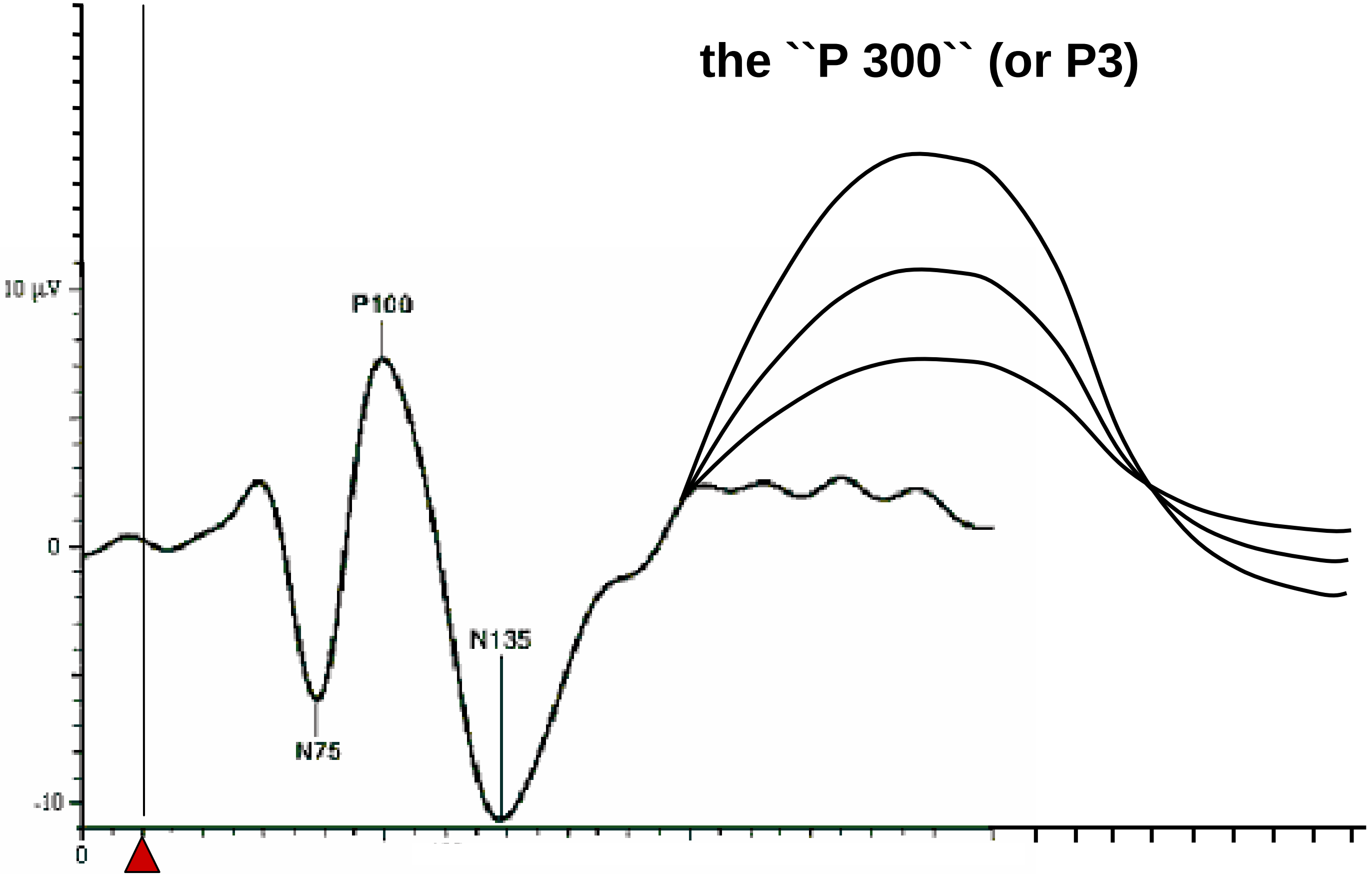
  - is generated by a specific stimulus, i.e. visual or auditory cue.

  - elicited commonly in an "oddball" paradigm when a subject detects an occasional "target" stimulus in a regular train of standard stimuli.

  - only occurs if the subject is actively engaged in the task of detecting the targets.

  Its amplitude varies with the improbability of the targets. Its latency varies with the difficulty of discriminating the target stimulus from the standard stimuli (Picton 1992, discovered by Sutton et al. 1965)

P 300 Visually Evoked Potentials



visual stimulation **with cognitive relevance**

P 300 Visually Evoked Potentials

Cognitive relevance: What generates a large P 300 component?

- **I can detect the target stimulus out of a number of non-targets**
- **I draw more attention to the target stimulus than to the others**
- **I can recognize the target stimulus**
- **I am waiting for the target stimulus to appear**
- **The target stimulus contains more information than the non-target**
- **The target has any other property that makes it unique**

The 6 x 6 matrix speller, single character flash

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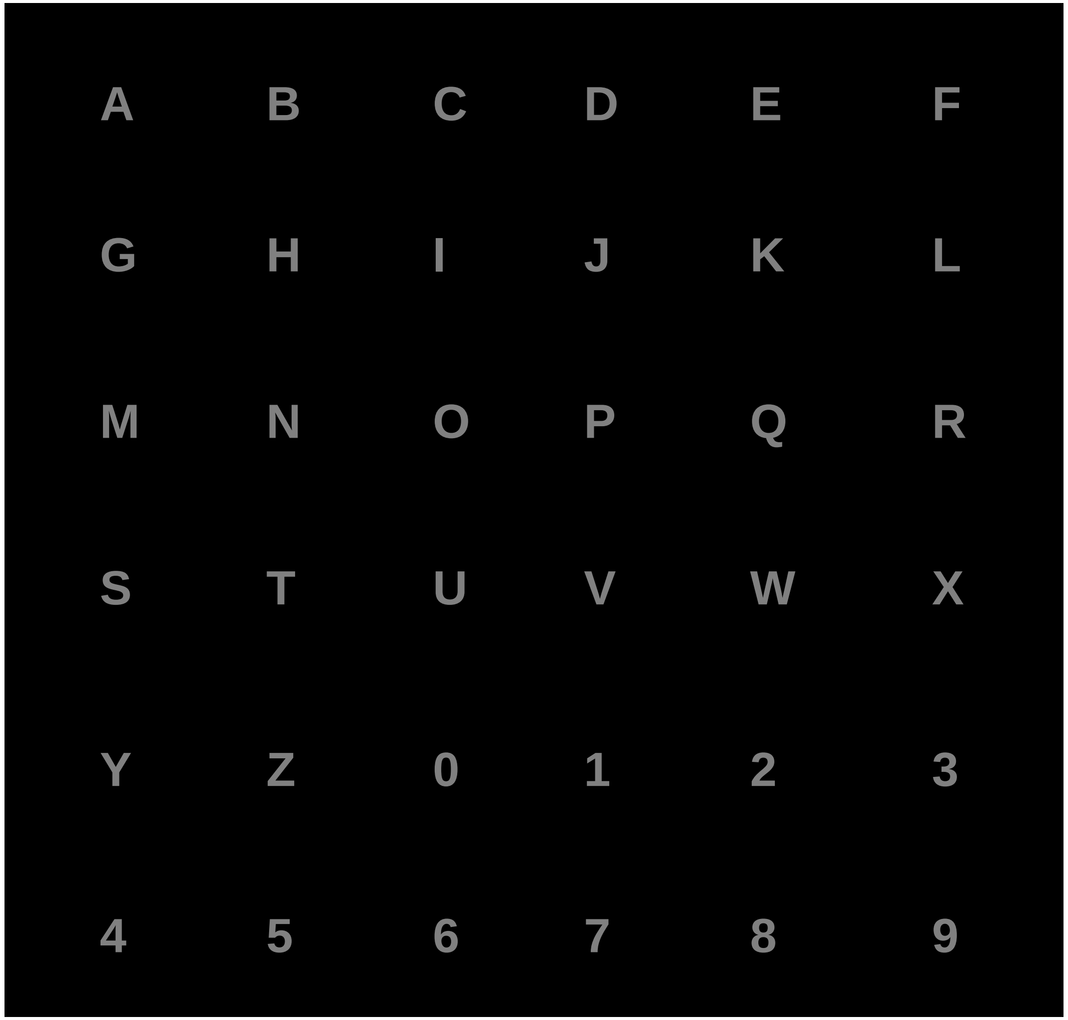
concentrate on „W“

Individual character intensifies for 60ms with 10ms between each intensification



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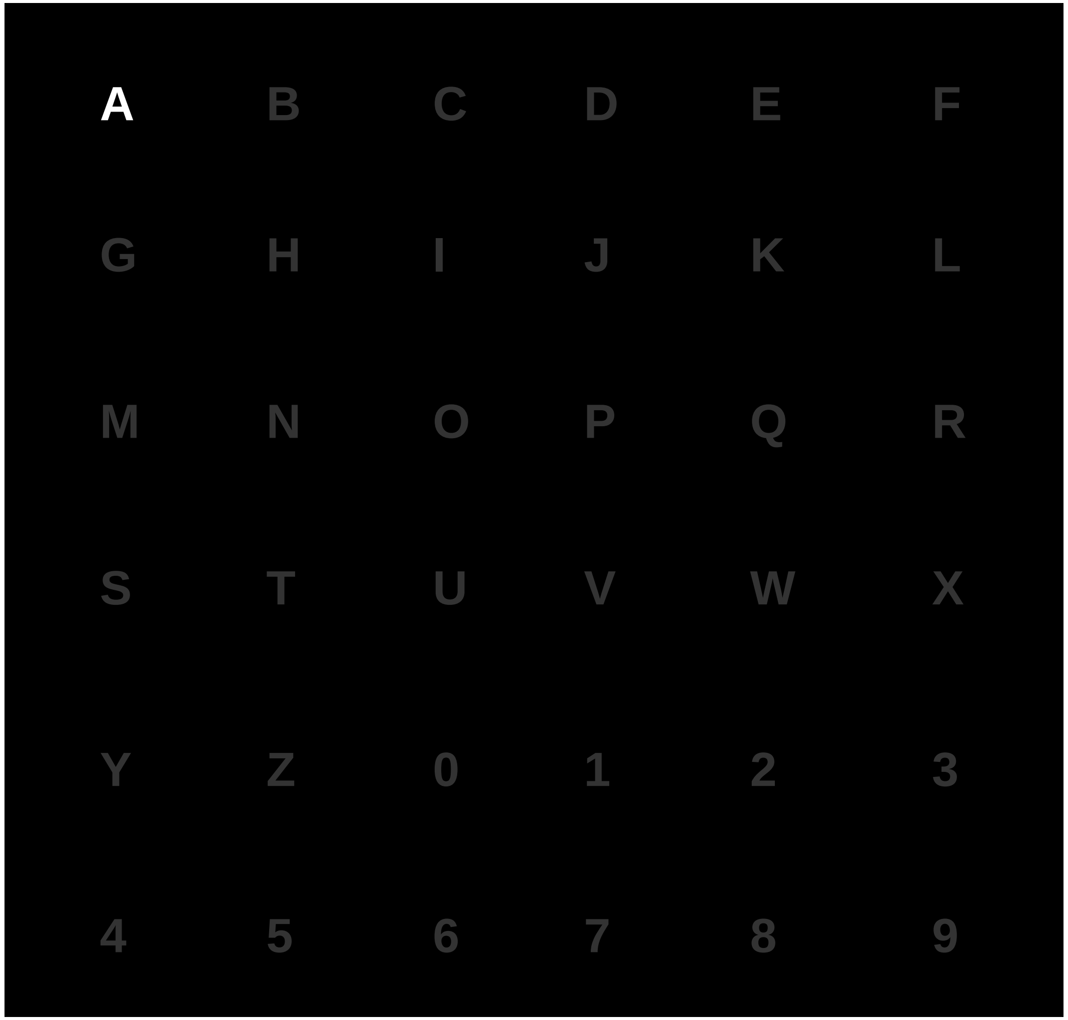
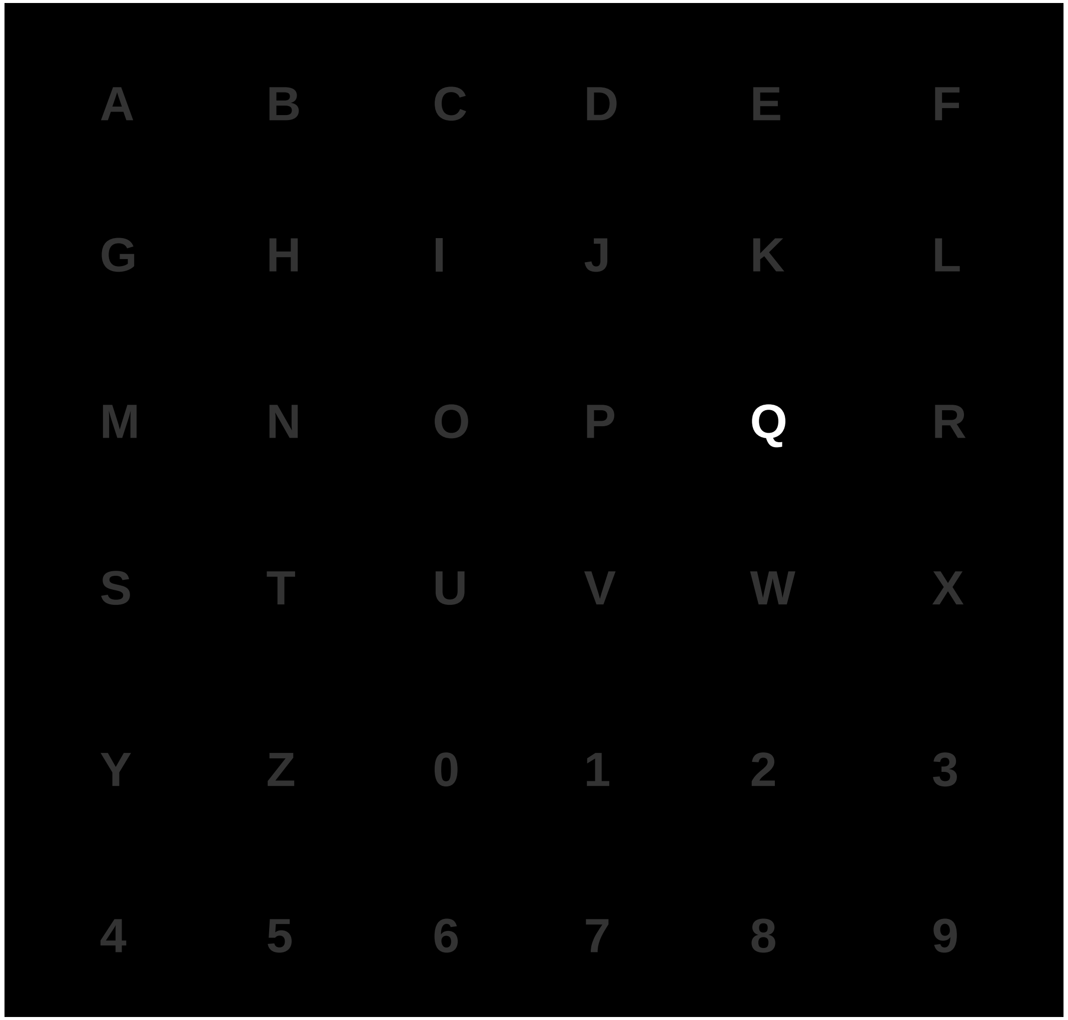
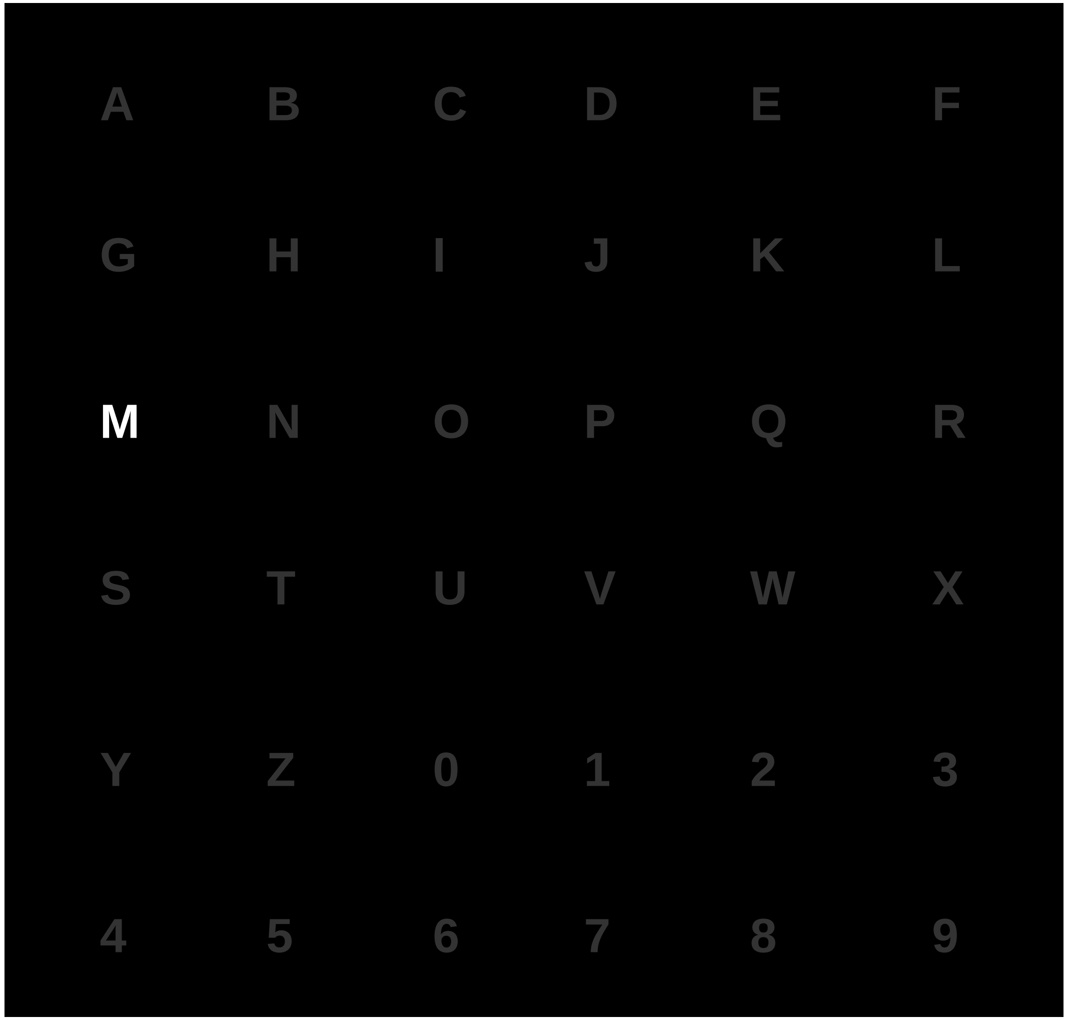
The 6 x 6 matrix speller, single character flash



The 6 x 6 matrix speller, single character flash



The 6 x 6 matrix speller, single character flash



The 6 x 6 matrix speller, single character flash

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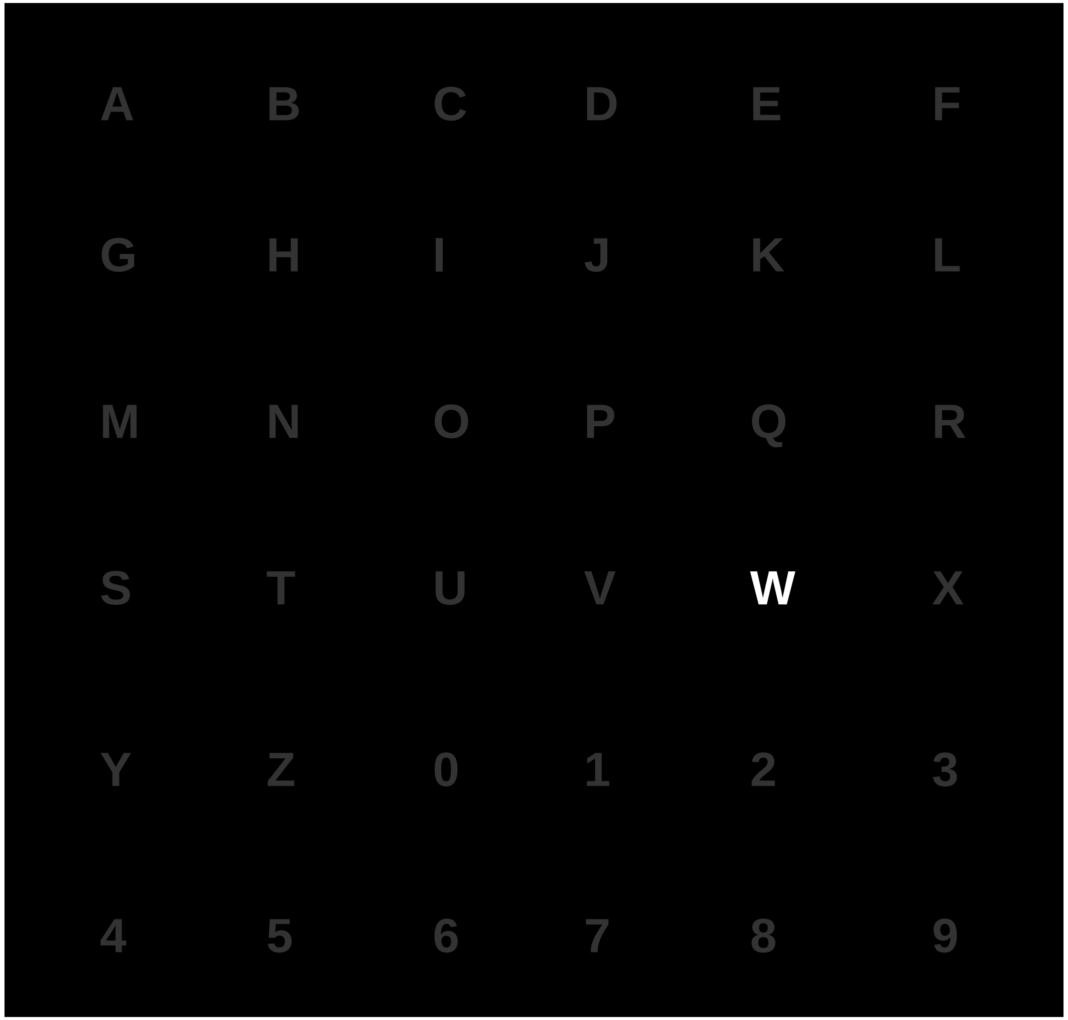

The 6 x 6 matrix speller, single character flash

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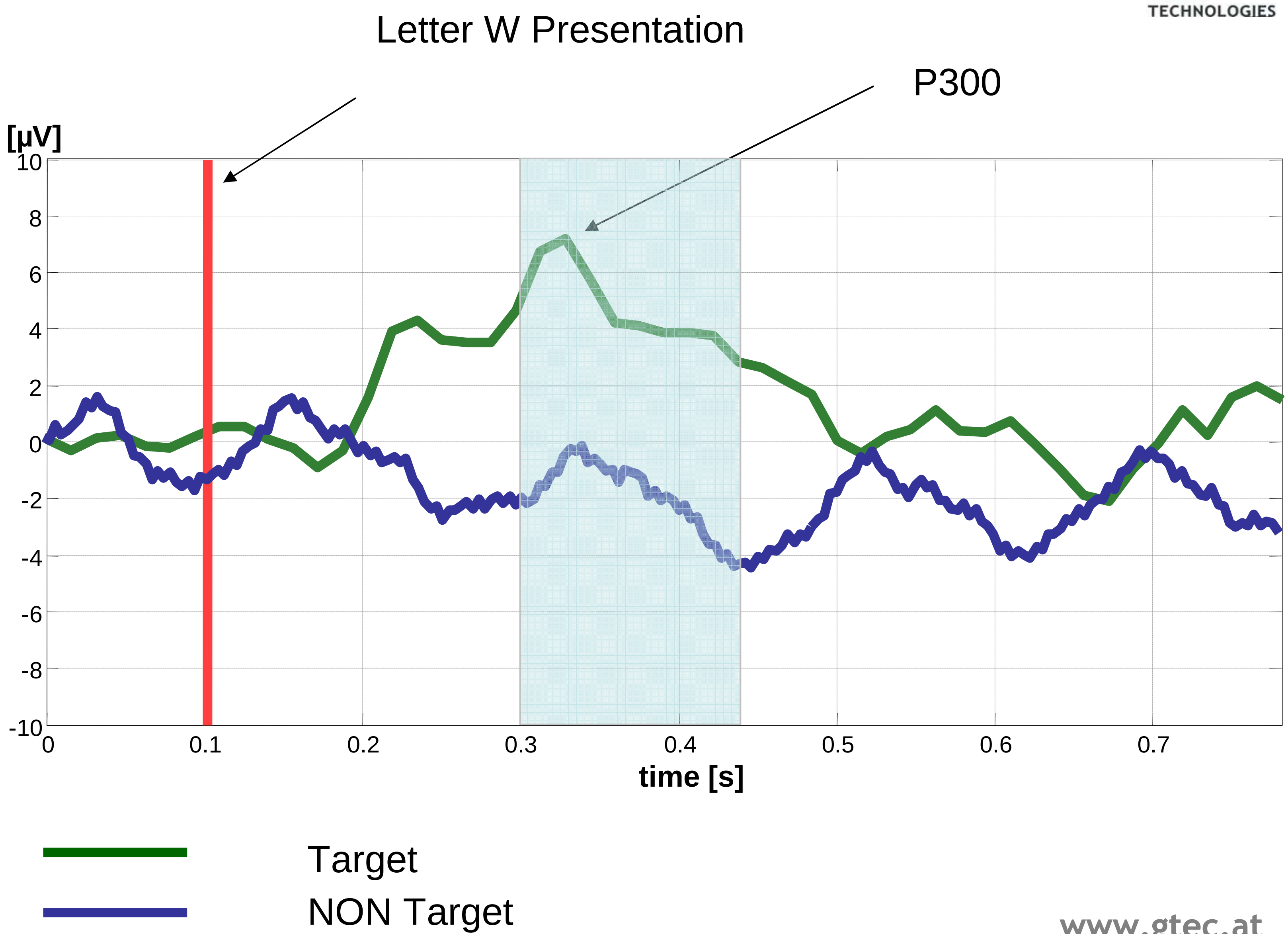

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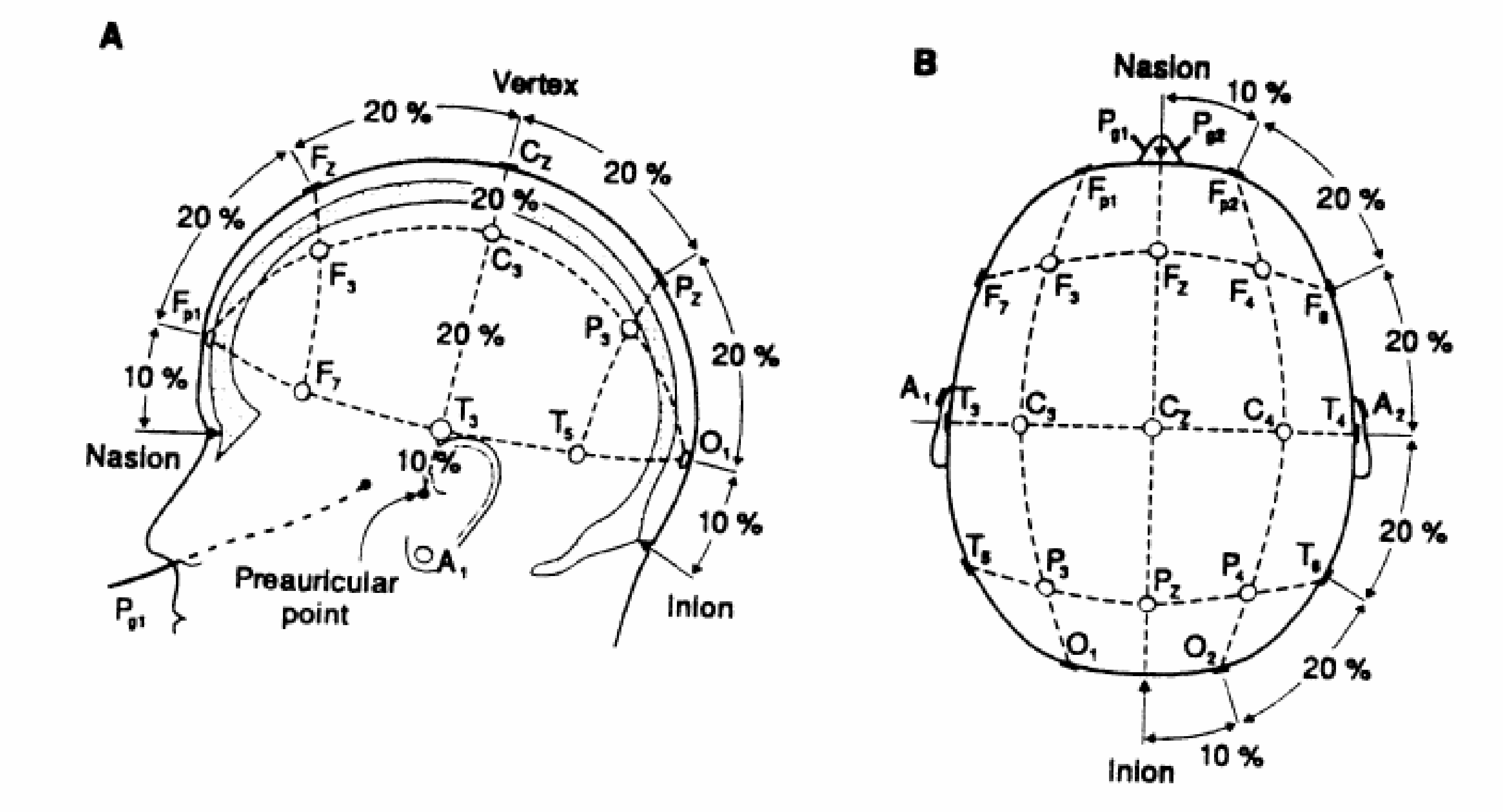
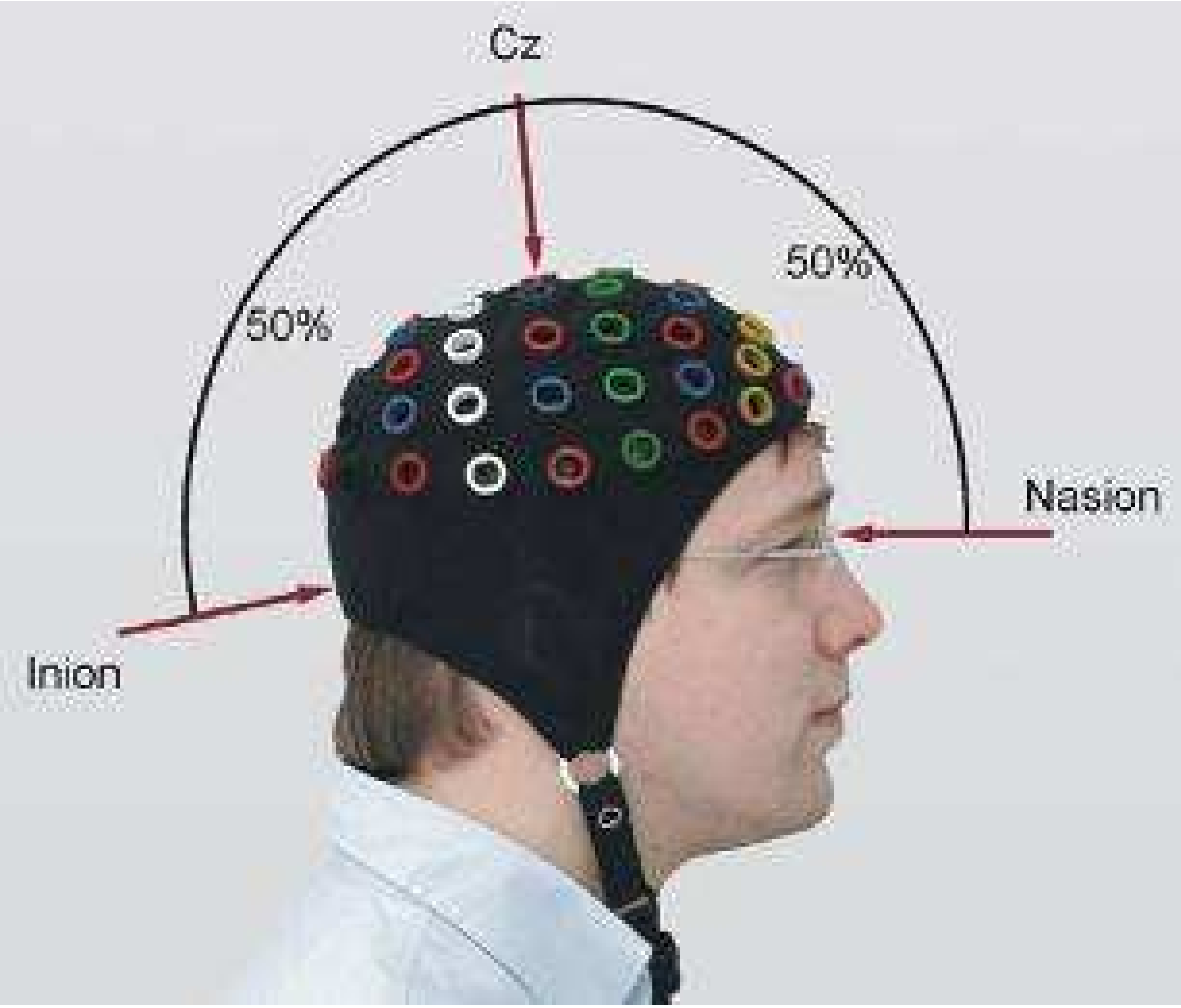
Mount electrodes



International 10/20 system. The distances between Inion-Nasion and the left and rigth preauricular points are the basis for the location of all electrode positions.

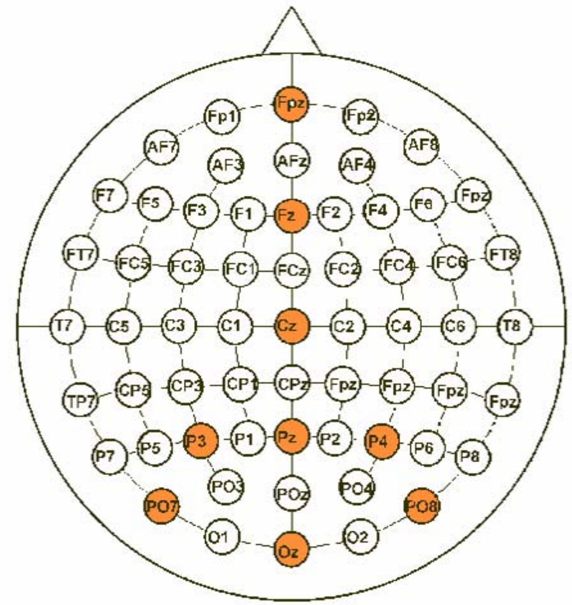
Placement of the cap



P300 BCI? Study Design

5 subjects, 8 EEG channels recorded

- Fz, Cz, P3, Pz, P4, PO7, Oz, PO8
- Referenced to right mastoid, grounded to the forehead
- Data recorded with g.USBamp



Fa = 256 Hz, bandpass 0.1 – 30 Hz

1st training run -> 5 letters

Application runs -> up to 42 letters

„Spelling Device“ Application

Single character flash experiment

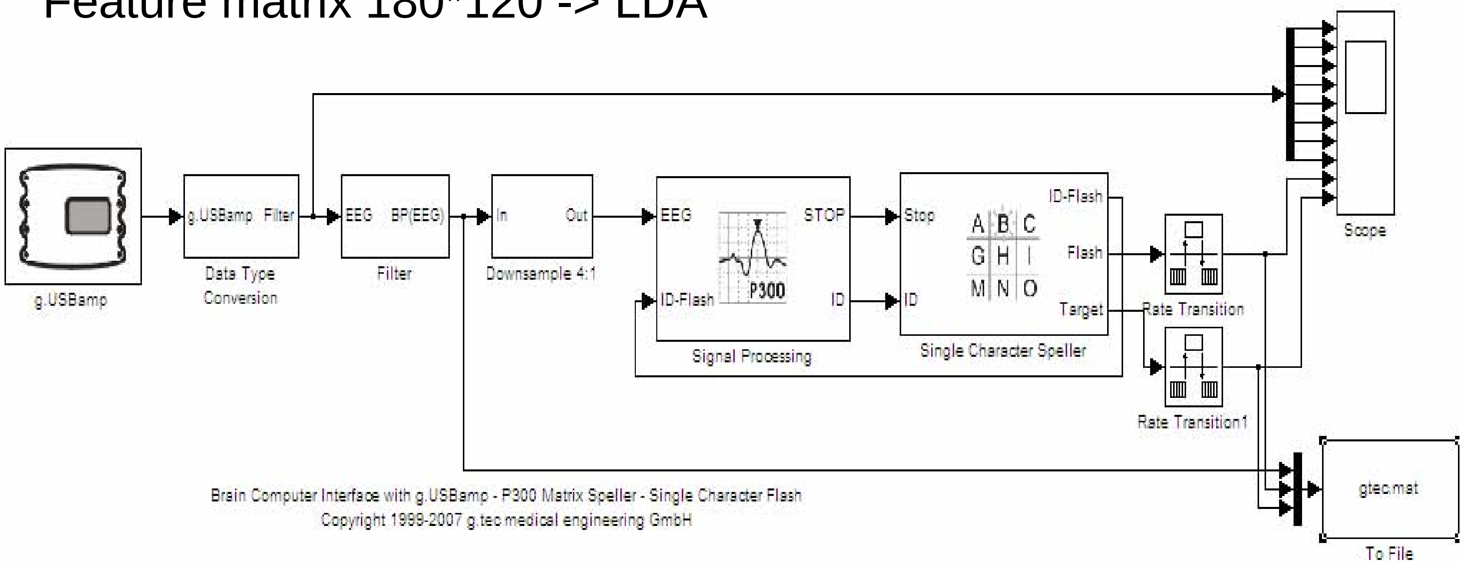
→ Total of ~ 45 min incl. electrode montage and instruction of the subject

Feature Extraction

Event related data triggering:
100ms pre-stimulus, 700ms post-stimulus
Baseline correction was performed for pre-stimulus interval
Downsampling (15 features/channel * 8 channel)
Data segments were concatenated by channel

Assume 5 flashes were selected for training, 3 letter word e.g. BCI
single character mode: 36*5 = 180 flashes * 3 repetitions
540 trials, 15 target trials, 525 non target trials

Feature matrix 180*120 -> LDA



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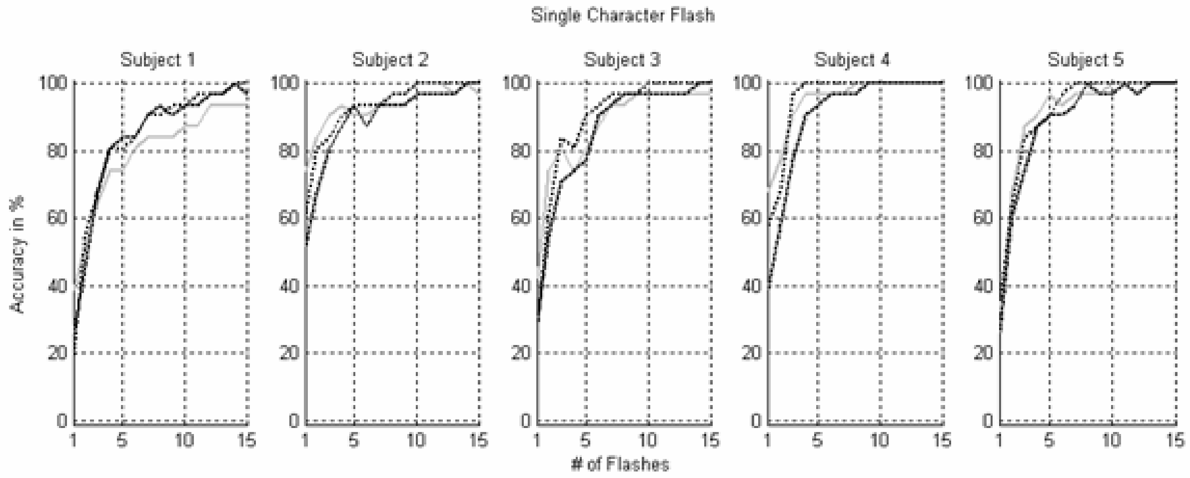
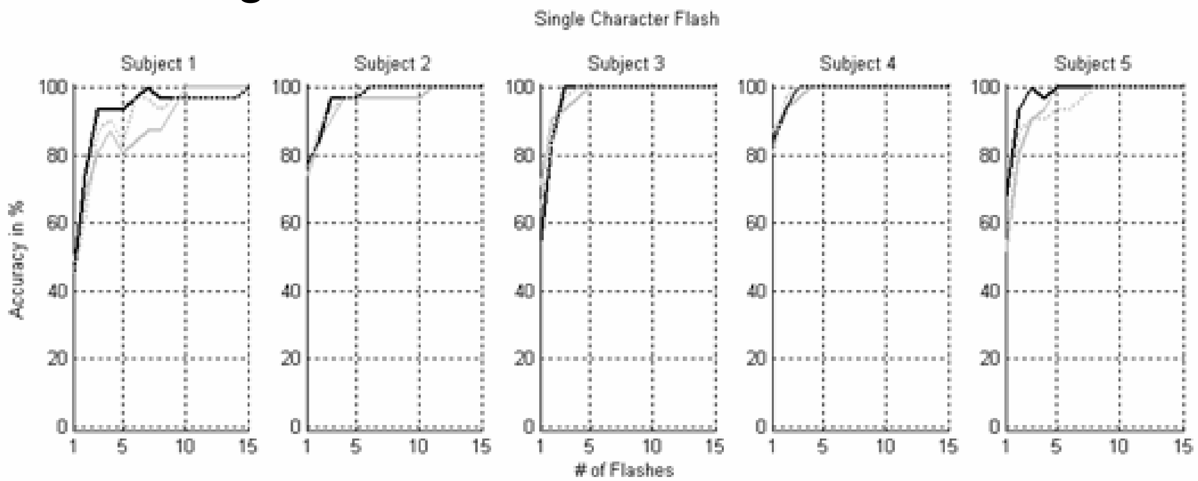
Accuracy depends on letters used for classifier training

3 training characters



42 training characters



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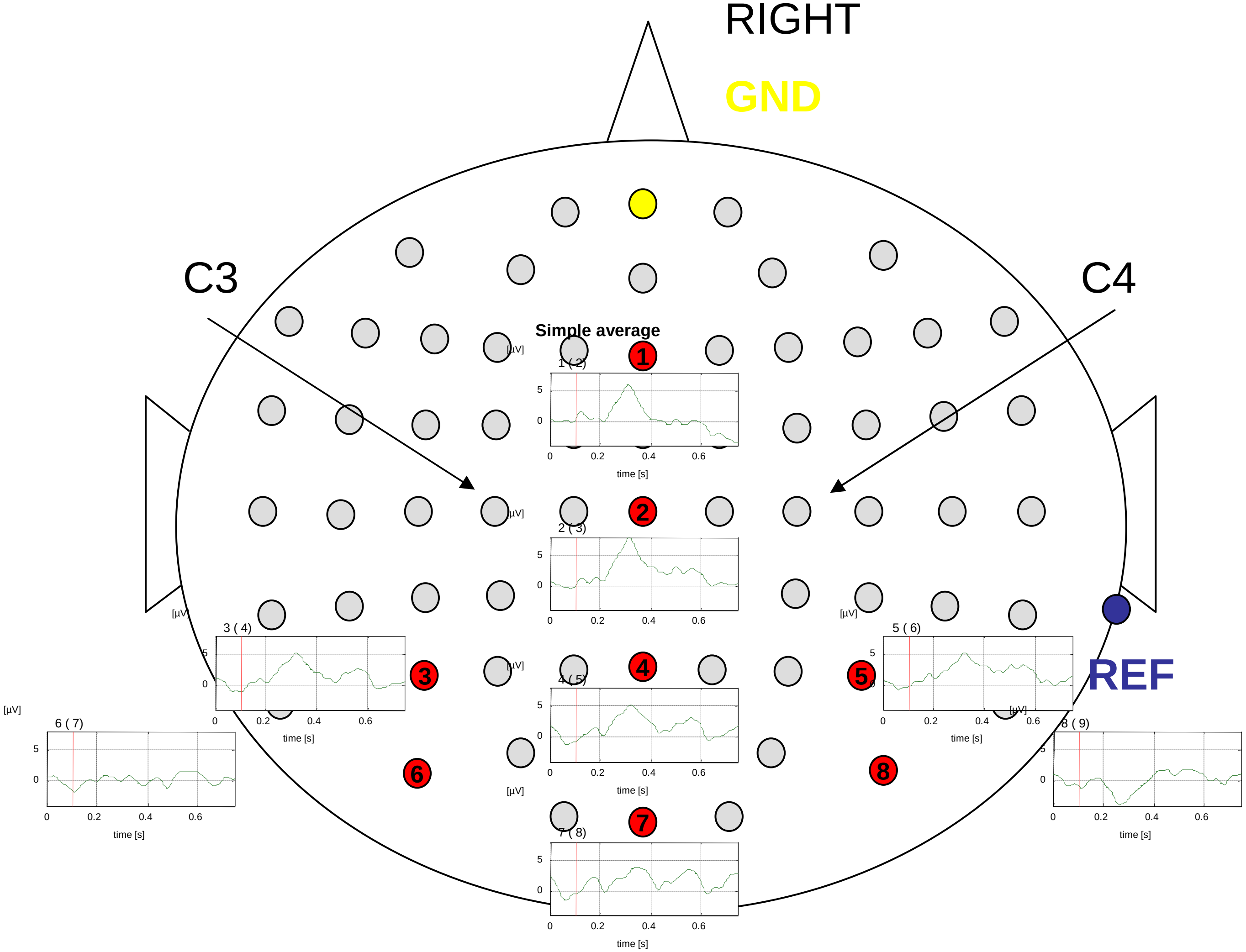
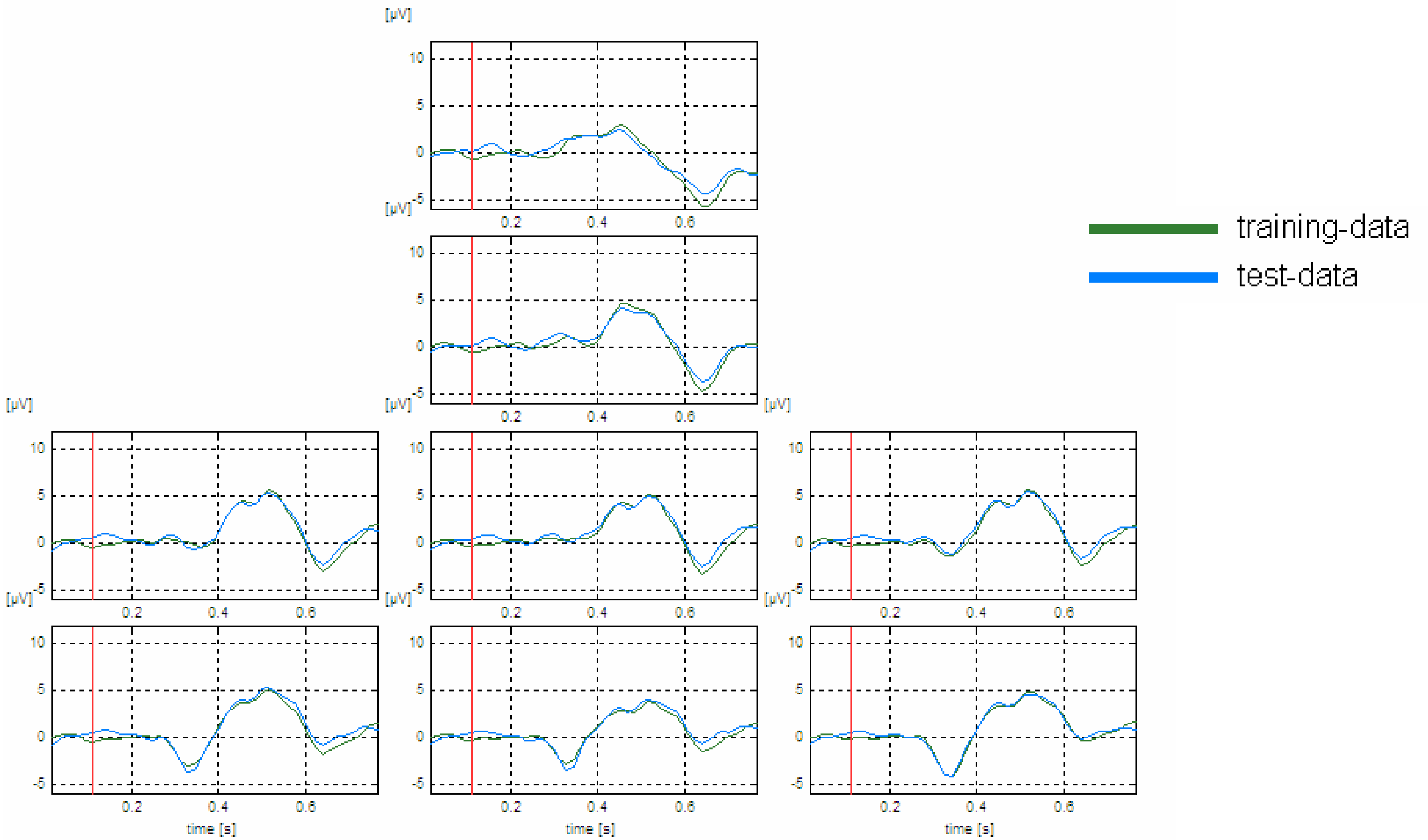
P300 Topography TARGET



Grand Average P300 responses

EP reaches about 5-6 µV, 350 ms after stimulus
No difference over time -> stable



Transfer rates calculation

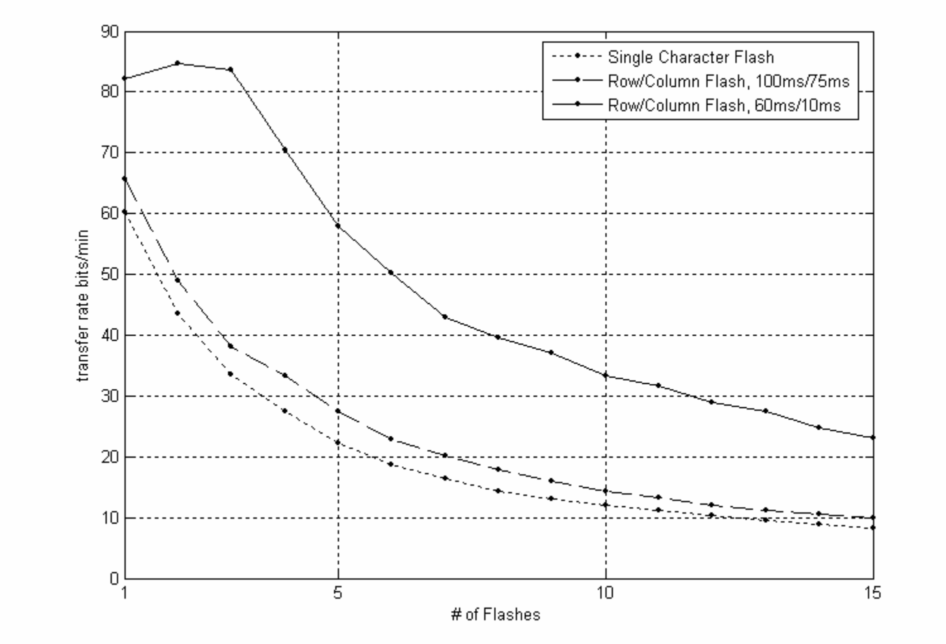
The bit rate R in bits/min is given by

$$R = B \cdot M$$

$$B = \log_2 N + P \cdot \log_2 P + (1-P) \cdot \log_2 \left[\frac{(1-P)}{(N-1)} \right]$$

where N is the number of possible selections, P is the accuracy probability and M is the average number of decisions per minute

Average transfer rates of all subjects



Neurofeedback Applications: P300 Speller, row/column flash
g.USBamp, g.MOBIlab, High-Speedonline Processing, g.RTanalyze, different sensors

Time [1:24]

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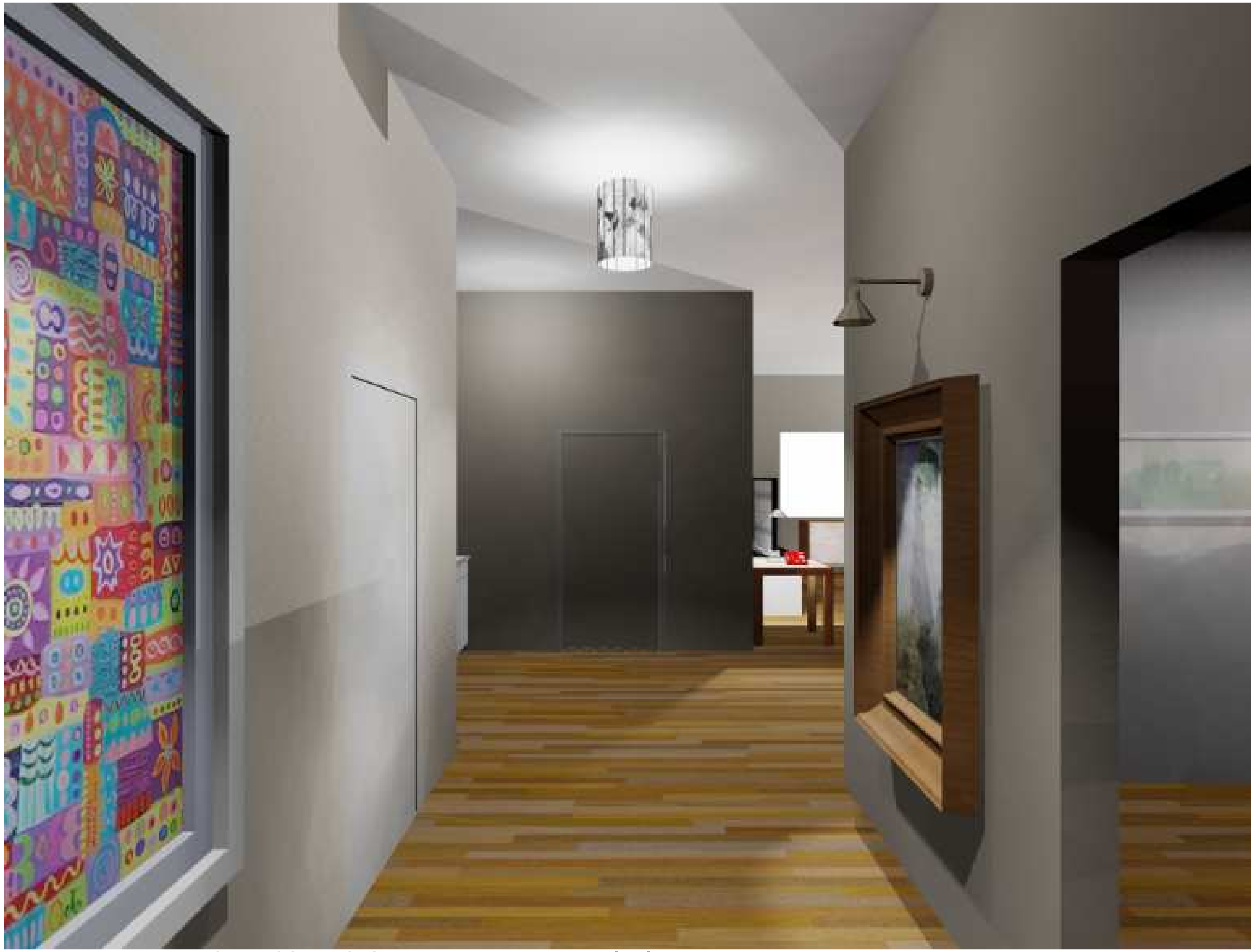
Live Experiment:
II) Smart Home Control XVR and BCI

P300 for smart home control

Designed by Chris Groenegress, Mel Slater

P300 for smart home control

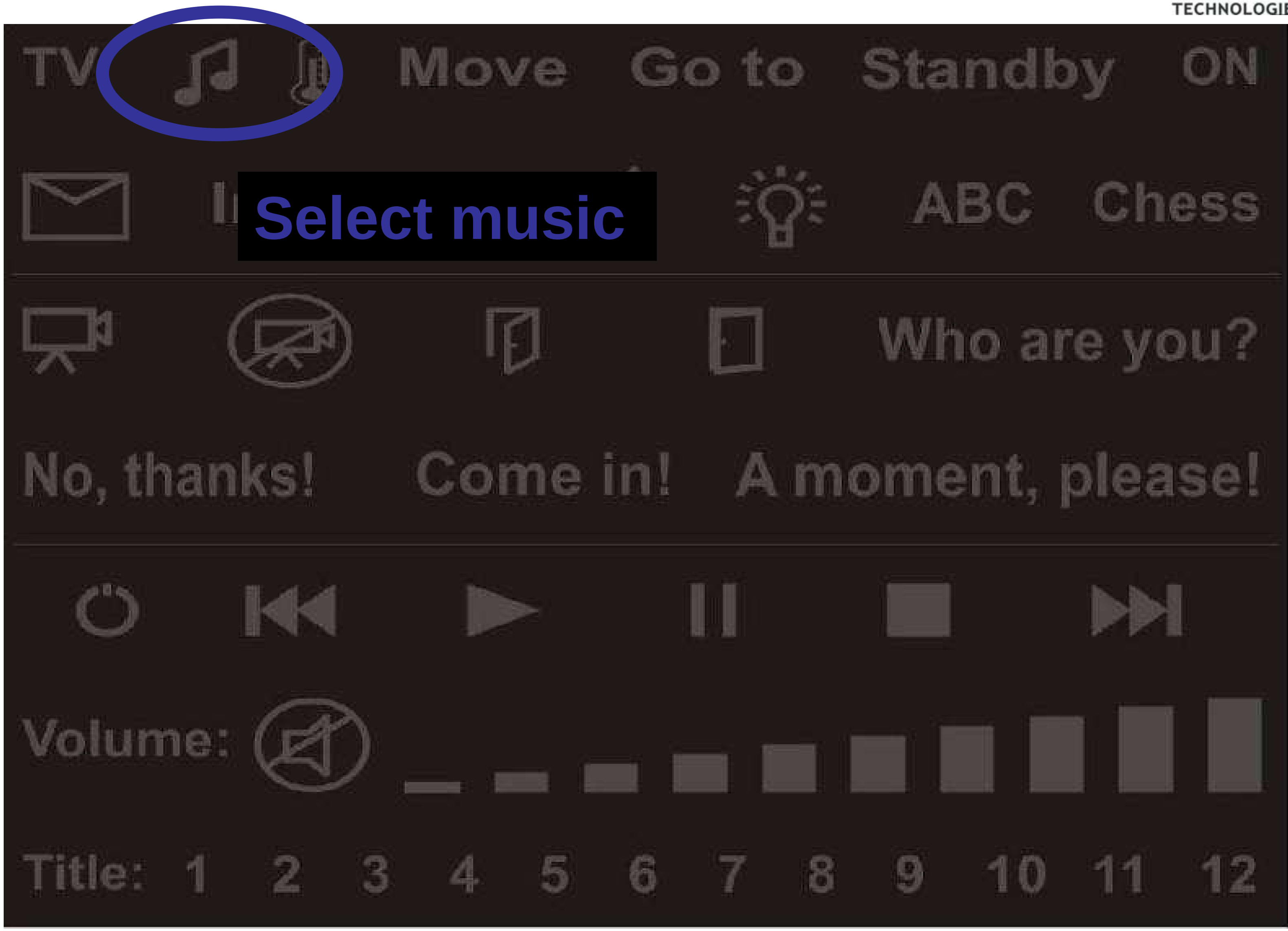


Designed by Chris Groenegress, Mel Slater

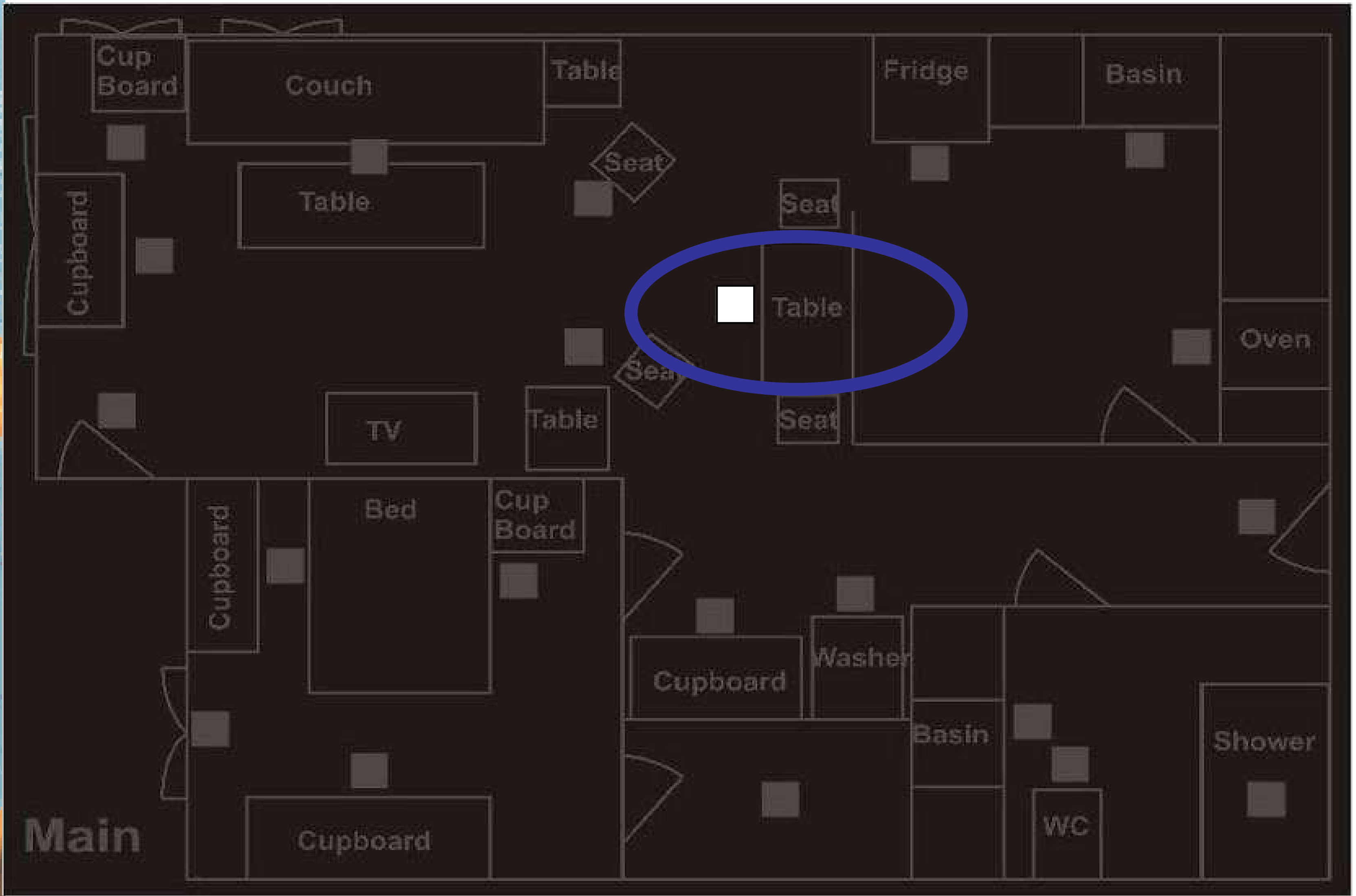
P300 for smart home control

Designed by Chris Groenegress, Mel Slater

Control matrix for smart home



Goto specific position – The Beamer



Discussion

The performance of a BCI system can be measured in terms of:

Decision speed (how many seconds are required for one decision?)
1-10 seconds for one decision with P300
same for osciallatory, SSVEP and slow waves

BUT

Degrees of freedom (how many classes can be selected?)

motor imagery task: max. 3 – 4 classes possible
slow cortical shift: continuous feedback for one dimension (up-down)
steady-state evoked potentials: up to 12 keys (phone keyboard)
P300-spelling: e.g. 36 letters (6 x 6 matrix) or more

P300 allows better control of smart home

Discussion

External visual stimuli
P300 need flashing characters -> it is not the thought of the subject

SSVEP – needs flickering light

Motor imagery BCI detect left/right hand movement, but there is also a trigger signal required that tells the subject when to think about the movement

Slow waves – need timing information

Accuracy (how many decisions are correct?)
Accuracy of 95 – 100 % possible for most subjects

Next steps:
Integration of the P300 BCI into highly immersive environment as a new way of communication

Some General Remarks:

- The Accuracy-vs.-Speed Problem (Transfer rate bit/min)

- Adaptive Algorithms: 2 Learning Systems !!!

- `State ot the Art`: from Research to Practical Use

- Acceptance & Usability: Evaluation by Patients and Caregivers

- Assets and Drawbacks of BCI compared to other Interfaces

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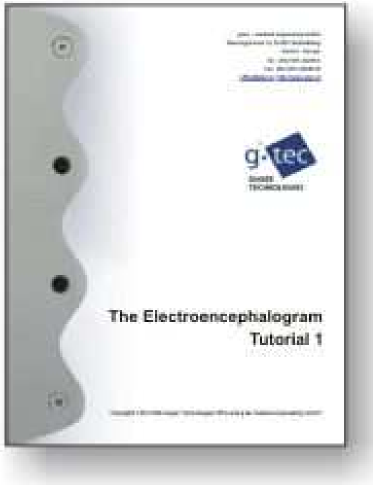
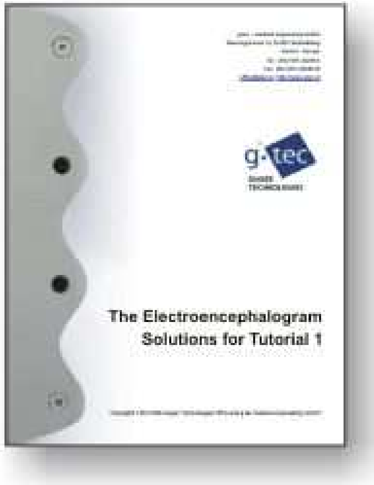
Potential for Further Improvement

Parameter Extraction Methods	Classification Algorithms	**Improved Sensors and Electrodes**
Implanted Sensors with Wireless Transmission	**Combination of different Methods**	New Applications
Online-Statistics for Optimized Decision Speed	Artifact Reduction Methods	**Assistive Systems: Text Completion, Speech output, ...**

Biomedical Engineering Lectures in PDF format

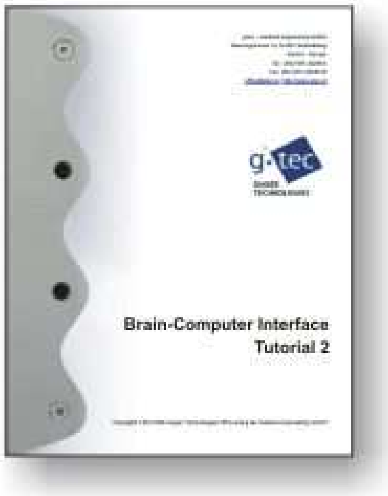


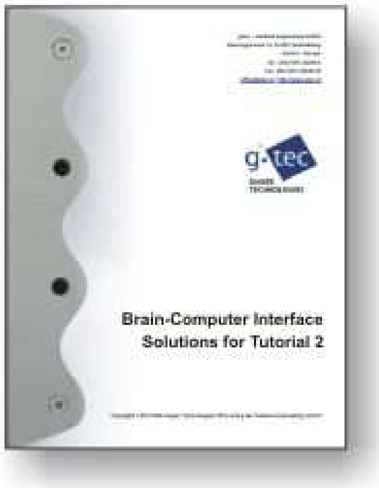


Tutorial contain theory and tasks (measurements, analysis,…)

Solutions in a second manual

Very useful in education and to get into the field





FREE AVAILABLE

BCI WORKSHOP Graz, Austria

g.tec BCI Workshop

TU Graz BCI Conference

September 2008

150 people

BCI Workshop @ Neuroscience, Washington DC, USA

November 2008

We have open positions for PHD students and master students.

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