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BCI-FES Rehabilitation System and Stroke Patients' EEG Data Analysis

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Outline

- Background
- Introduction to BCI-FES Rehabilitation System
- Experiment Set-up and Data Acquisition
- Rehabilitation Training
- Data Analysis Methods
- Results and Mechanisms
- Future Work

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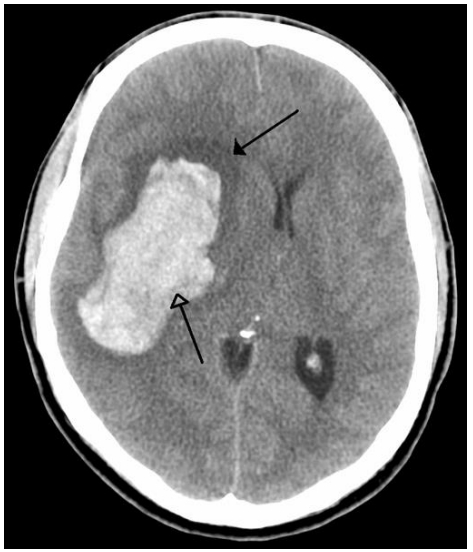
Stroke and Disability

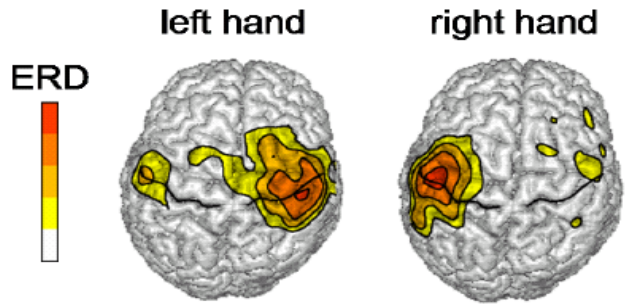
- A leading cause of adult disability
- Affect physically, mentally, emotionally or a combination of the three
- Rehabilitation Therapeutic Avenues
  - **Motor re-learning**
  - **Mental Practice/Mental Imagery**
  - **Functional Electrical Stimulation**
  - **Mirror Therapy**
  - **Constraint-induced movement therapy**

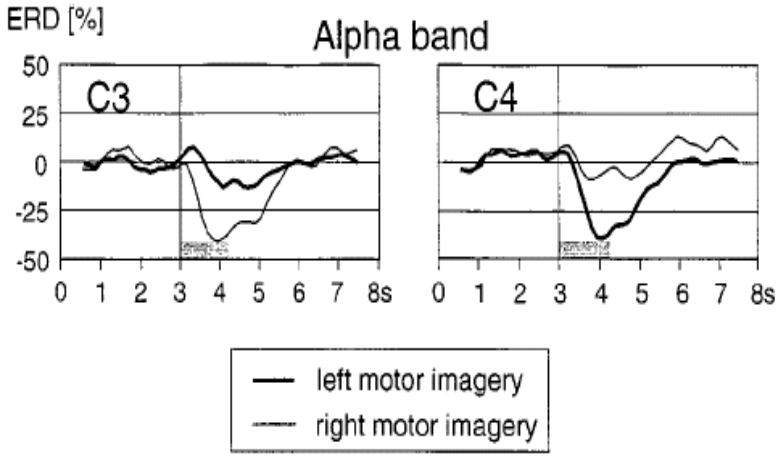


From wikipedia, James Heilman, MD

Neurophysiological Fundamentals

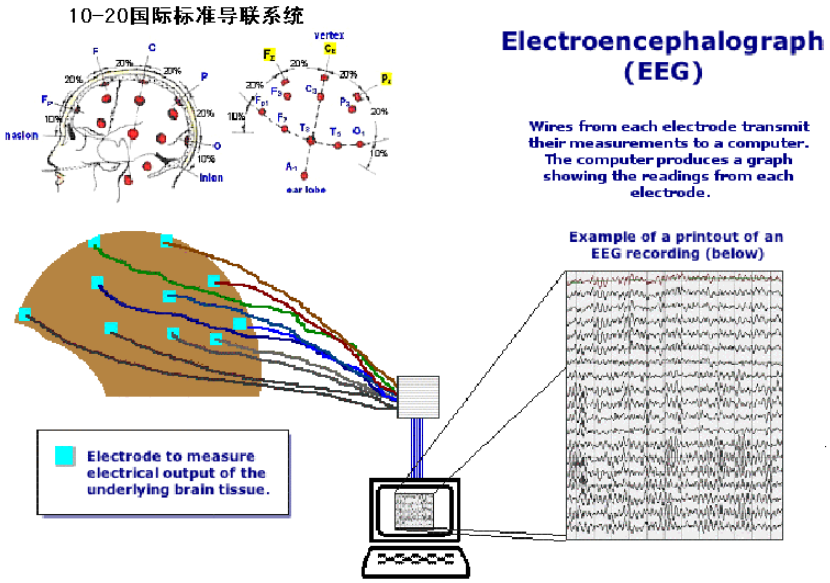
- The event-related desynchronization and synchronization (*ERD/ERS*)
- ERD/ERS (Mu and beta rhythm)
  - Self-paced imagery movement





EEG Acquisition

- The 19-channel g.USBamp amplifier is adopted in our research(Non-invasive).



Common Spatial Pattern

- Two Class Problem

$$\Sigma_1 = \sum_{j \in C_l} \frac{\mathbf{E}_j * \mathbf{E}_j^T}{trace(\mathbf{E}_j * \mathbf{E}_j^T)}, \quad \Sigma_2 = \sum_{j \in C_r} \frac{\mathbf{E}_j * \mathbf{E}_j^T}{trace(\mathbf{E}_j * \mathbf{E}_j^T)},$$

- Objective Function

$$\mathbf{w}\Sigma_1\mathbf{w}^T = \mathbf{D}, \qquad \mathbf{w}\Sigma_2\mathbf{w}^T = \mathbf{I} - \mathbf{D},$$

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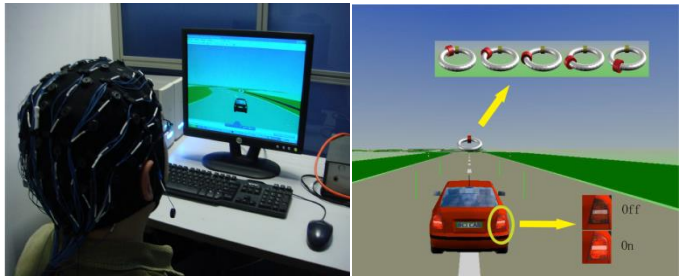
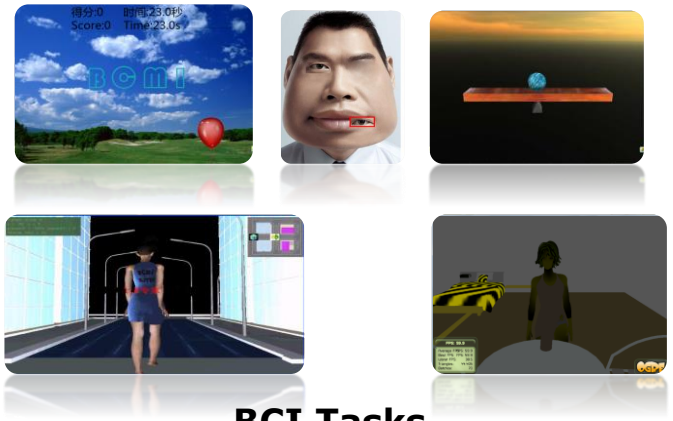
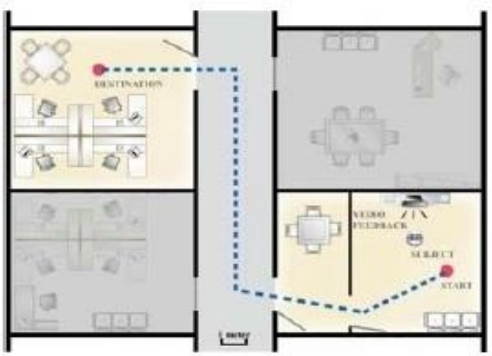
BCI Applications

- BCI Car-Driving Systems
- BCI Wheelchair System
- BCI Remote Control System
- BCI Based Rehabilitation for Stoke Patients





BCI Tasks



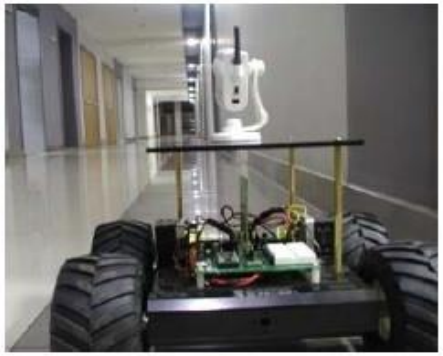
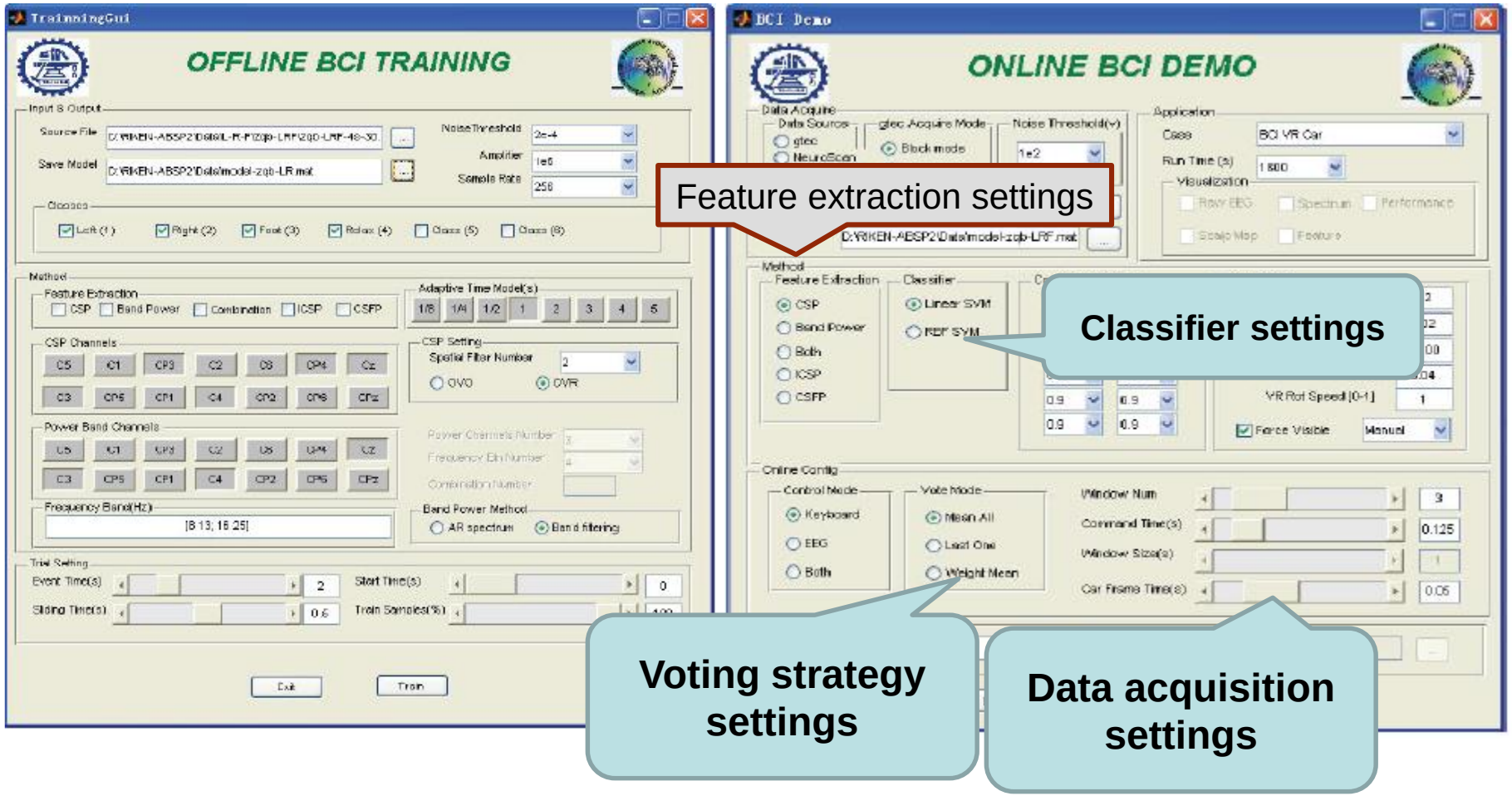
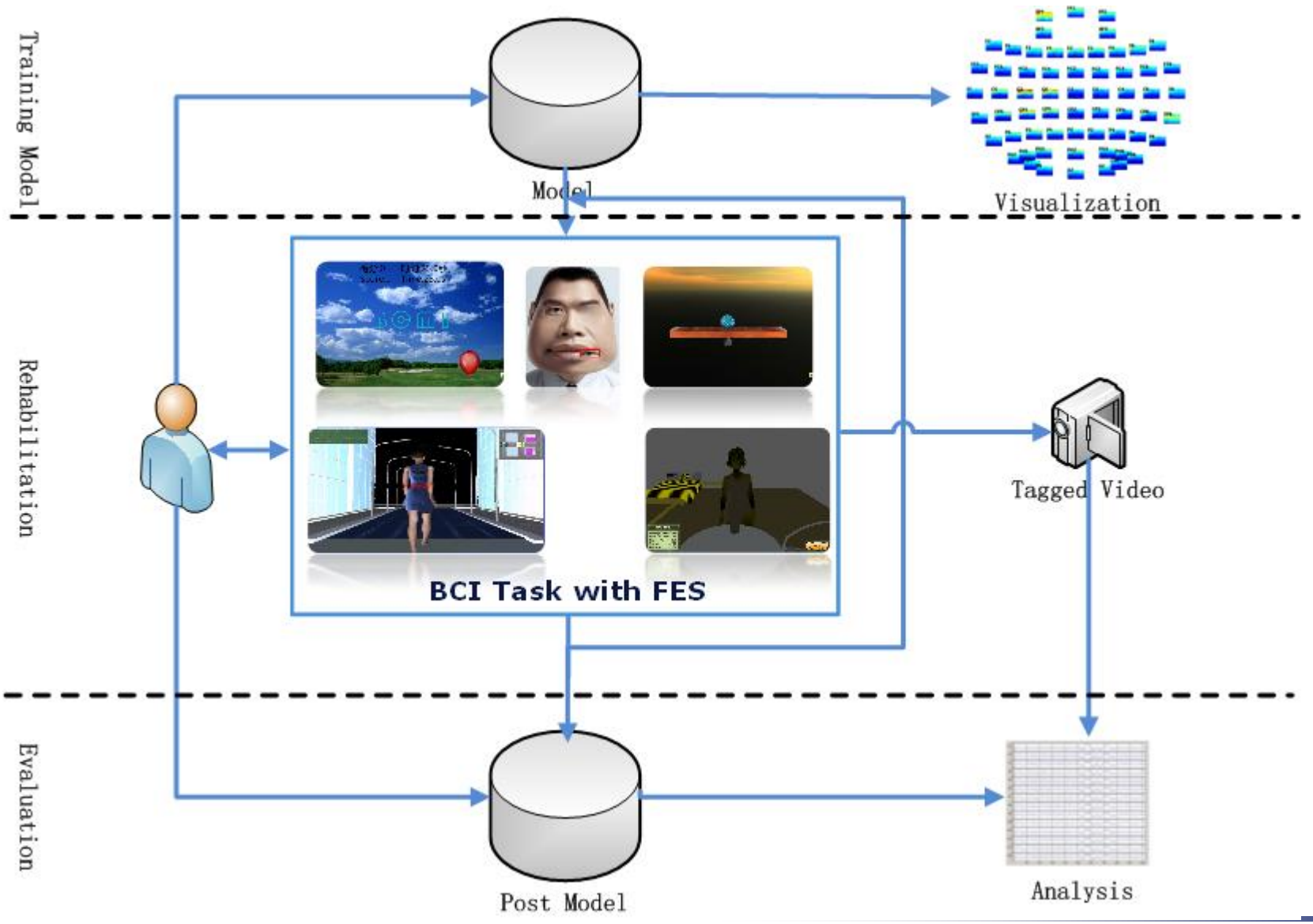


图 4-2 在线远程机械车驾驶

SJTU-BCMI BCI System



Motor Functional Rehabilitation Paradigm



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Goal

- Effective Rehabilitation System
- Rehabilitation / EEG Database
  - Tagged Videos
  - EEG Data: Training / Rehabilitation / Post Training
  - MEG / fMRI Data
- Research
  - Causal relation of FES and ERS/ERD
  - Neurophysiologic Mechanism
  - Principles of Physiology

BCI-FES Rehabilitation Training

- Three procedures:

1. Prior training offline:

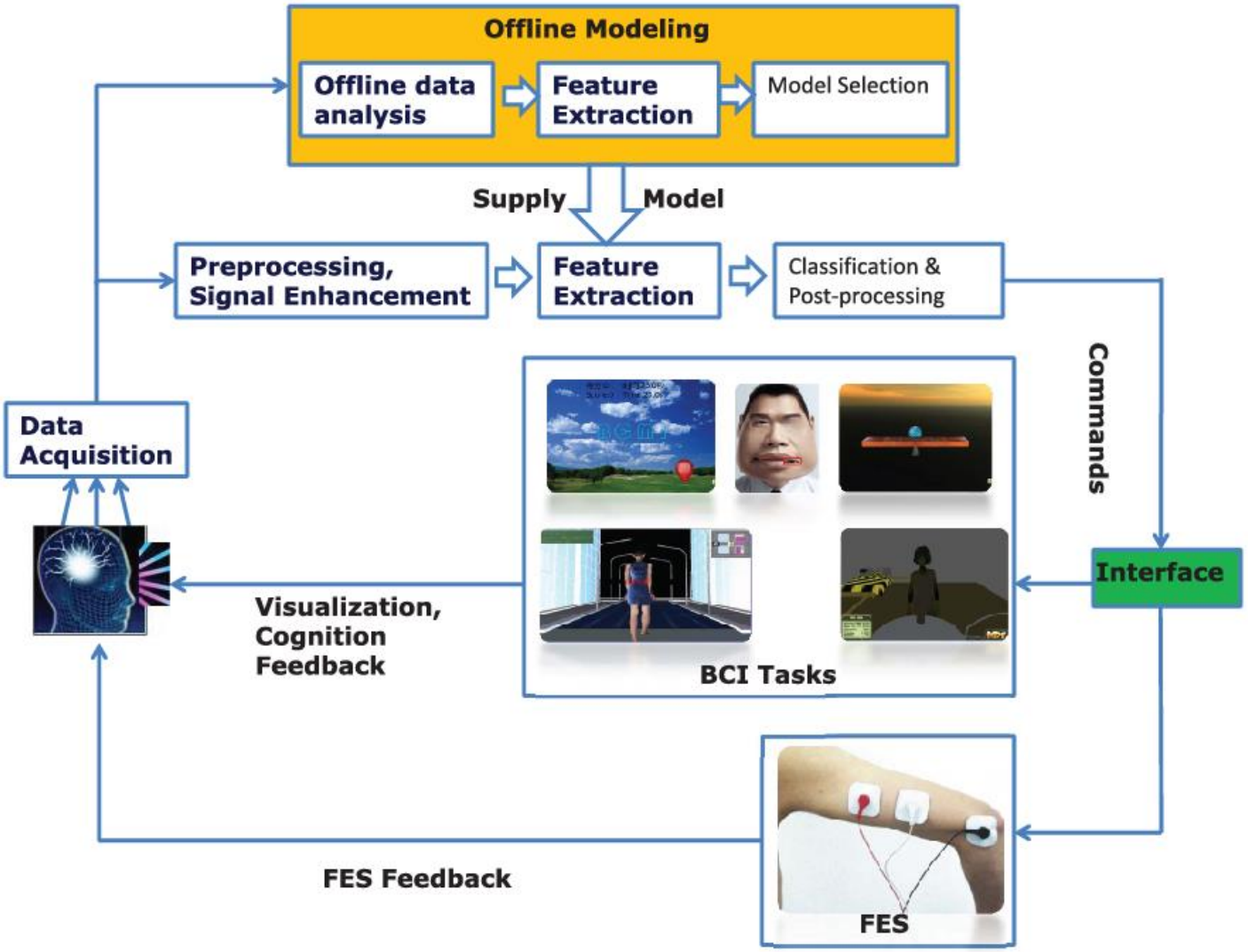
   The first session data is used for training a prior model;

2. Training and rehabilitation tasks;

   With FES stimulations;

3. Post training for assessment.

Global View


Offline Modeling
Offline data analysis
Feature Extraction
Model Selection
Supply
Model
Preprocessing, Signal Enhancement
Feature Extraction
Classification & Post-processing
Commands
Data Acquisition
Visualization, Cognition Feedback
BCI Tasks
Interface
FES Feedback
FES

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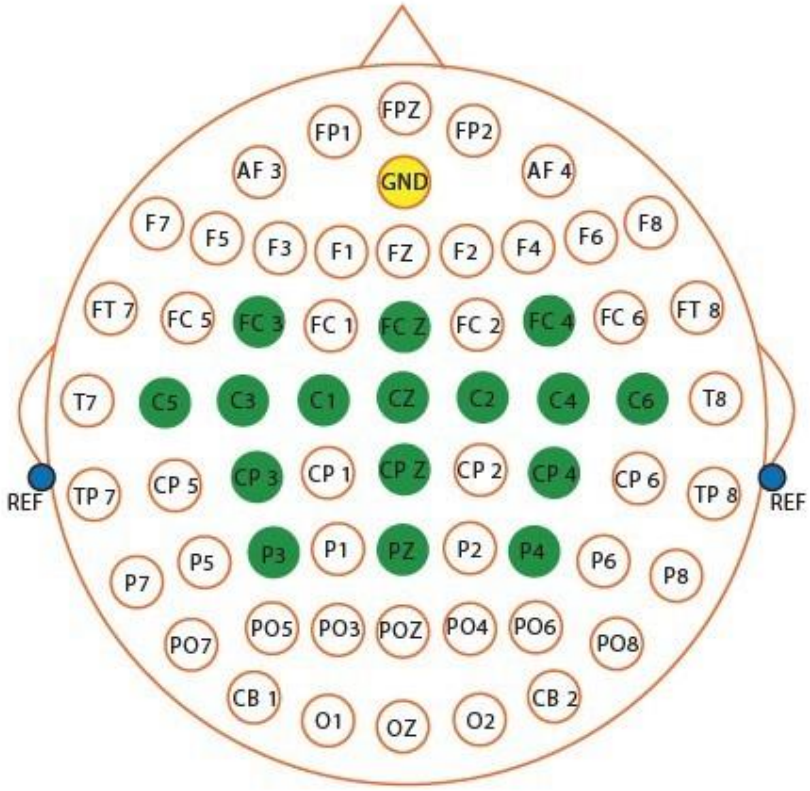
Subjects Recruitment

- Hemiplegia was caused by first time cerebal hemorrhage or infarction, and verified by CT (Computerized Tomography) or fMRI (Functional Magnetic Resonance Imaging);
- The paralytic subjects should be between 35 and 75 years old without gender restriction;
- Onset time should be between 2 weeks and 9 months, because this period is the perfect rehabilitation time for stroke in pathology;
- Subjects have no problem in cognitive ability.

Experiment Set-up

- Positions of the 19 selected channels. The two post-ear ones (marked blue in the figure) are averaged as the reference lead.



Positions of the 19 channels
Yellow —— ground
Blue —— reference

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Data Acquisition

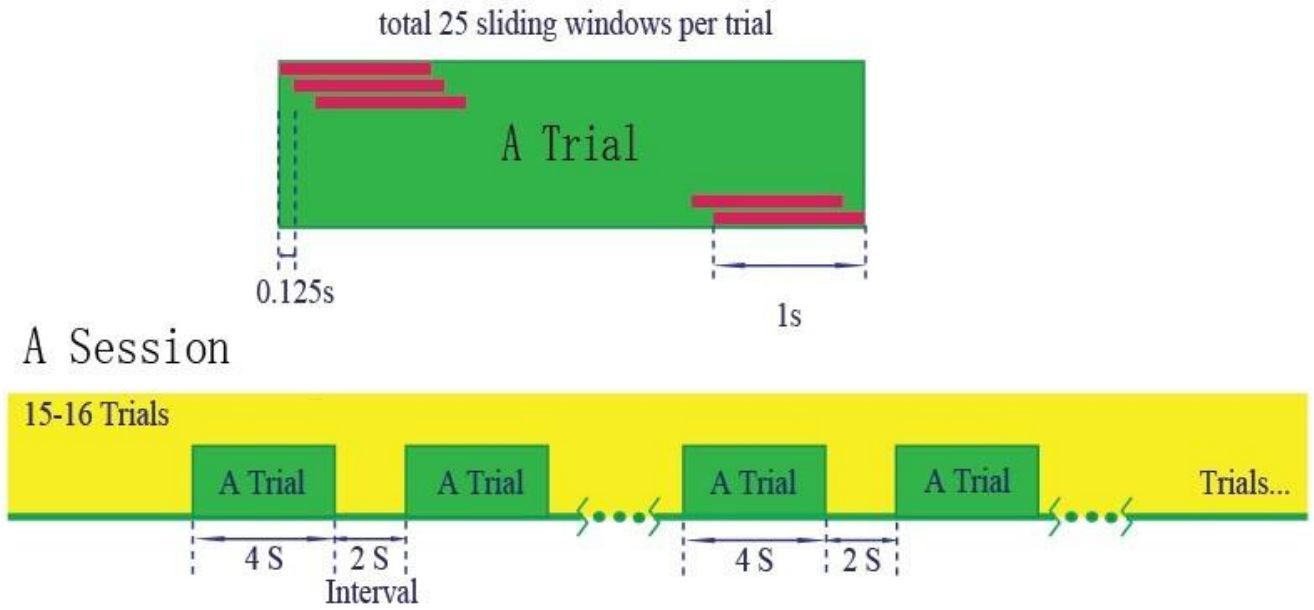
- subjects are required to take part in different numbers of sessions ranged from 5 to 8 per day and 3 days per week;
- Each session contains 15-16 numbers of 4 seconds trials including close number of left and right motor imagery tasks;
- Time sequences of each trial are cut into 25 sliding windows with size 1s and step length 0.125s as shown;
- After pre-processing and feature extraction, the sliding windows are put into an online classifier (trained in the prior-training process);
- Voting strategy is employed to determine the class of the whole trial.

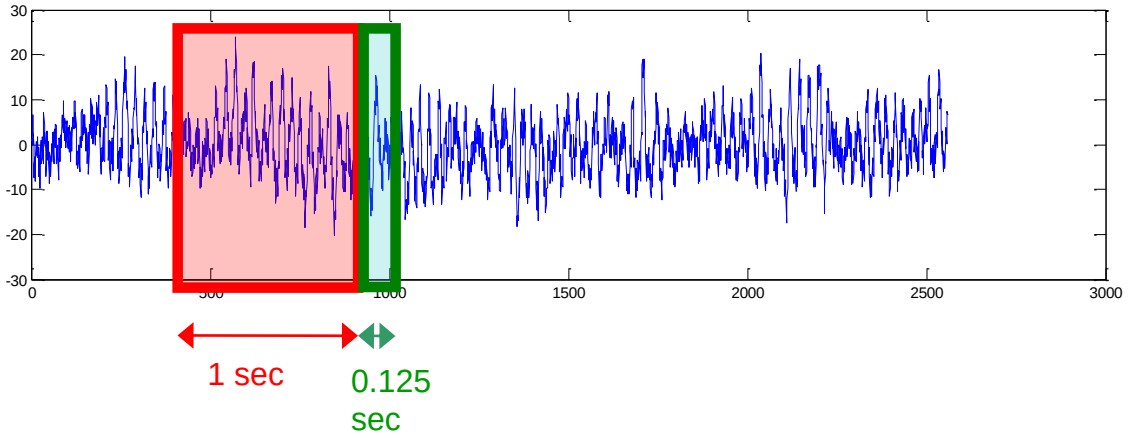
Experiment Set-up

- Important Parameters

Parameter	Value
Number of channels	19 (3 for reference and ground)
Sampling rate	256Hz
Frequency band	8 – 30 Hz
Number of trials per session	15 – 16
Time per trial	4 seconds
Sliding window size	1 second
Sliding windows step length	0.125 second
Dimensions of feature	4

Data Acquisition





Classification

- Voting strategy

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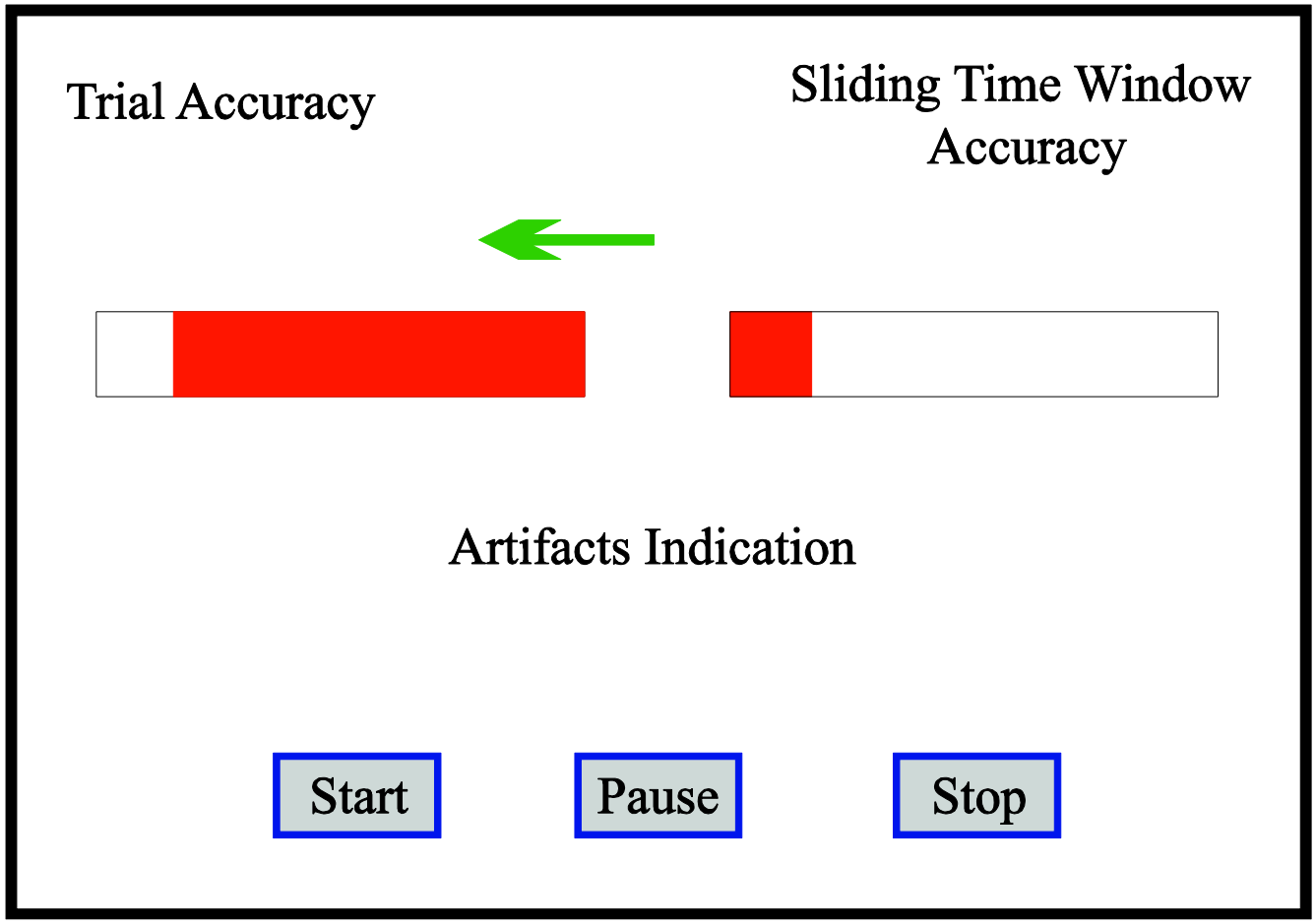
Prior - training

- Easy: 2–class motor imagery;
- Difficult: 3-class motor imagery;
- The motor imagery EEG data of the first prior session will be used for training a prior-model offline.
- In most cases, we will not insert FES stimulations in this session.

Prior - training

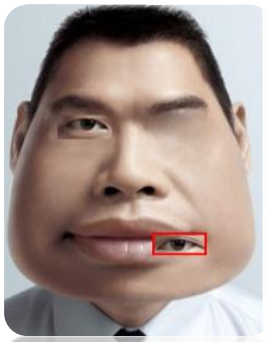
- Two-class prior-training task



Rehabilitation tasks

- Subjects are asked to finish some motor imagery based games like balancing a beam or lifting balloons appeared randomly in the left or right part of the screen;
- FES is triggered and stimulates subjects' muscles under an appreciate current when they get stuck, which causes real movement of their hands or arms;

BCI Rehabilitation Tasks



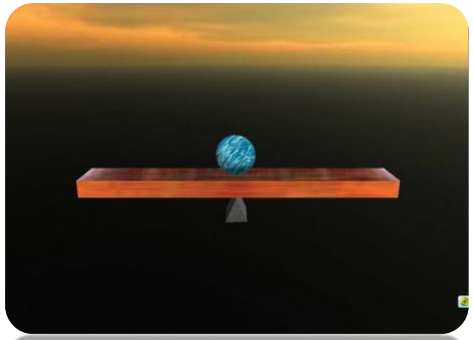
Basic

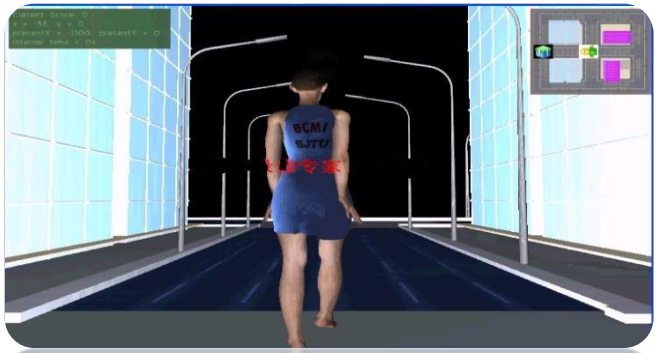
Cognition

Complex

Challenge

Daily Life





BCI Rehabilitation Tasks

- Combinations of FES Stimulations and Mental Practice/Mental Imagery;
- The imagination-stimulation process reconstructs the neuroncircuit between paralysis limbs and corresponding pathological brain area of the subject and takes effects in the rehabilitation treatment.
- Multimodal stimulations like sight, auditory sense and touch sense could be inserted.

Post – training process

- A post-training session with 16 trials is finished for rehabilitation efficacy assessment;
- No FES stimulation;

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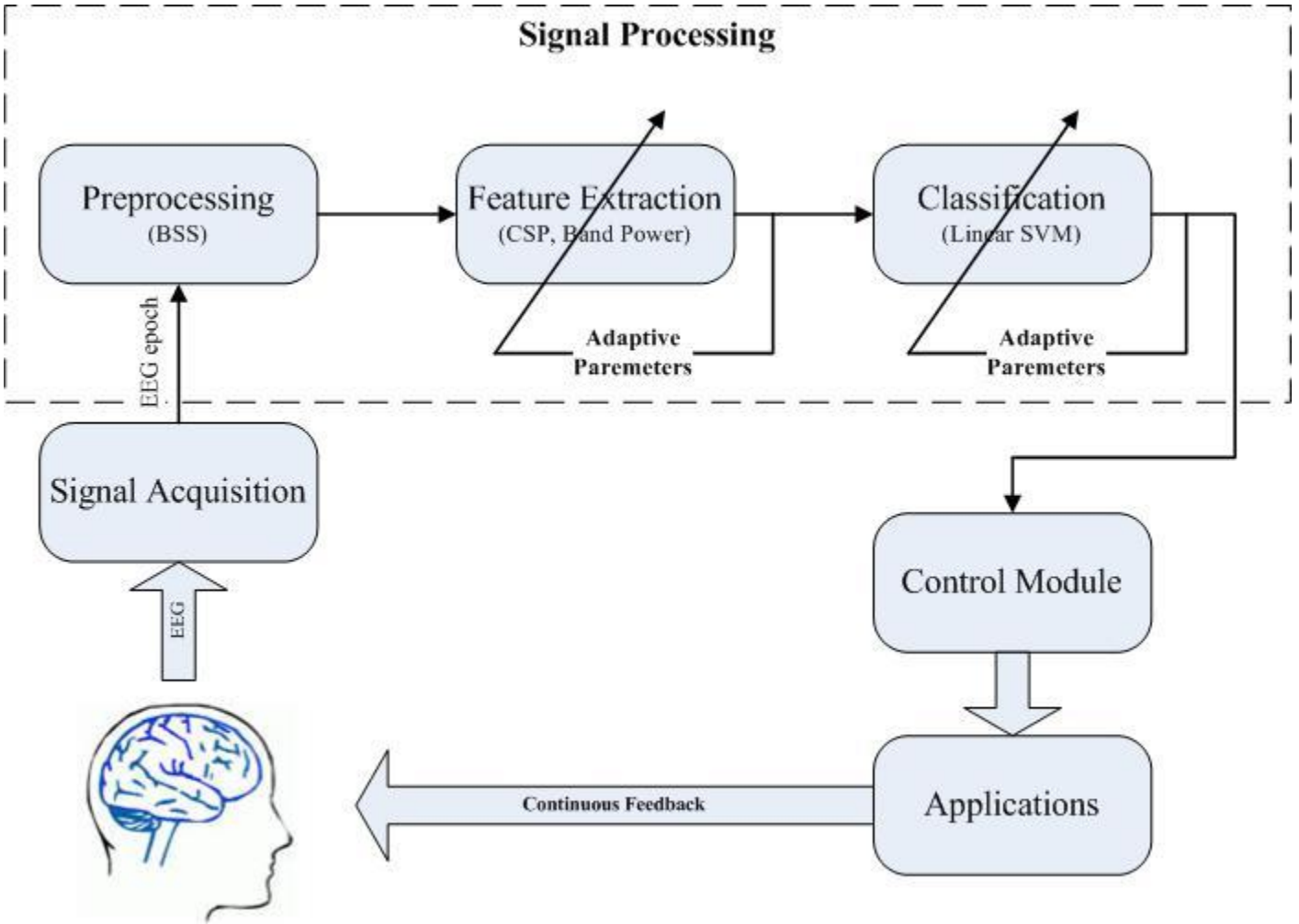
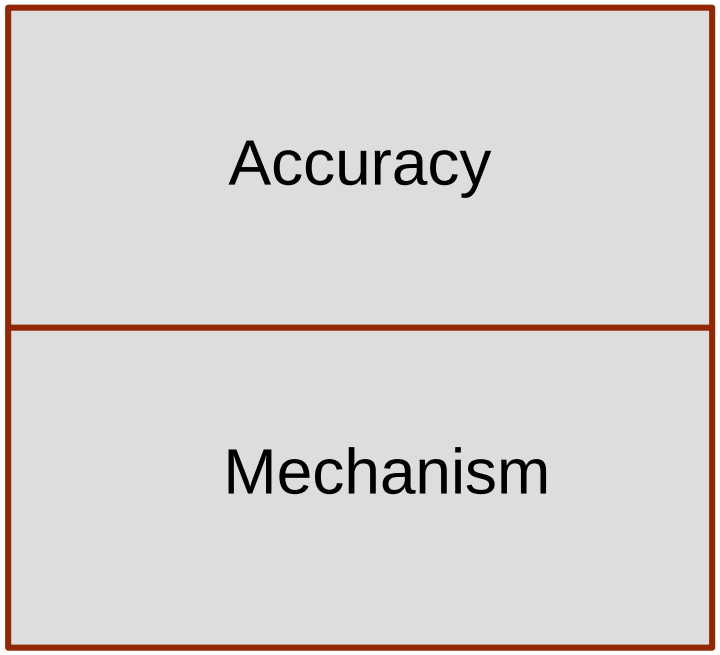
Global View


Signal Processing
Preprocessing
(BSS)
Feature Extraction
(CSP, Band Power)
Classification
(Linear SVM)
Adaptive
Paremeters
Adaptive
Paremeters
EEG epoch
Signal Acquisition
EEG
Control Module
Applications
Continuous Feedback

Data Analysis Methods

- Key Problems:



Data Analysis Methods

- General CSP
- Iterative CSP
- Gaussian Mixture Model Filter
- Frequency Boost
- Mixed Dataset Test
- Re-score
- Dynamic Pattern Recognition Methods

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General CSP

- Common Spatial Pattern
- Feature extraction method in EEG
- First proposed by H. Ramoser in “Optimal Spatial Filtering of Single Trial EEG during Imagined Hand Movement”
- Commonly applied for calculating an optimal direction which maximizes the differentiation of two kinds of mental states in EEG

General CSP

$$Z = VE \tag{1}$$

Signals with largest eigenvalues maximize the difference of variance of left versus right motor imagery EEG. These signals are the m first and last rows of Z. Normalization is done by using the following equation[5][9]:

$$f_p = \log\left(\frac{var(Z_p)}{\sum_{i=1}^{2m} var(Z_i)}\right) \tag{2}$$

Each window (explained in the following subsection) of EEG is transformed into a 4-dimensional feature in our experiment.

General CSP

- **Problems**

1. Mix regular motor imagery signals with unexpected noise such as failed, missed or mistaken imagery caused by injuries on corresponding brain areas and mental maladjustments;

2. General CSP may detect a wrong orientation when applied directly on this kind of datasets under the interference of irregular patterns;

3. Features with low discrimination are put into SVM/LDA classifiers, which leads to poor classification accuracy.

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Iterative CSP

- Motivation

I. Two models:

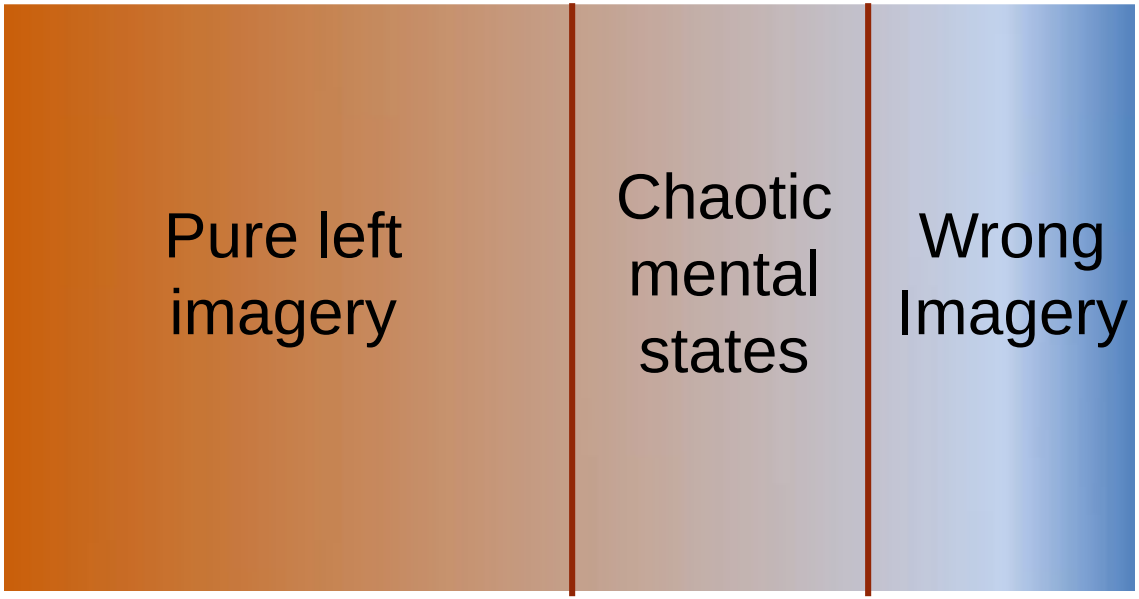
1. Left Model: classify left and non-left;
2. Right Model: classify right and non-right.

II. Three parts of Stroke patients' EEG data:

1. Pure part(75%): right motor imagery;
2. Chaotic part(15%~20%): miss/mixed ones;
3. Wrong part(5%~10%): wrong motor imagery.

Iterative CSP

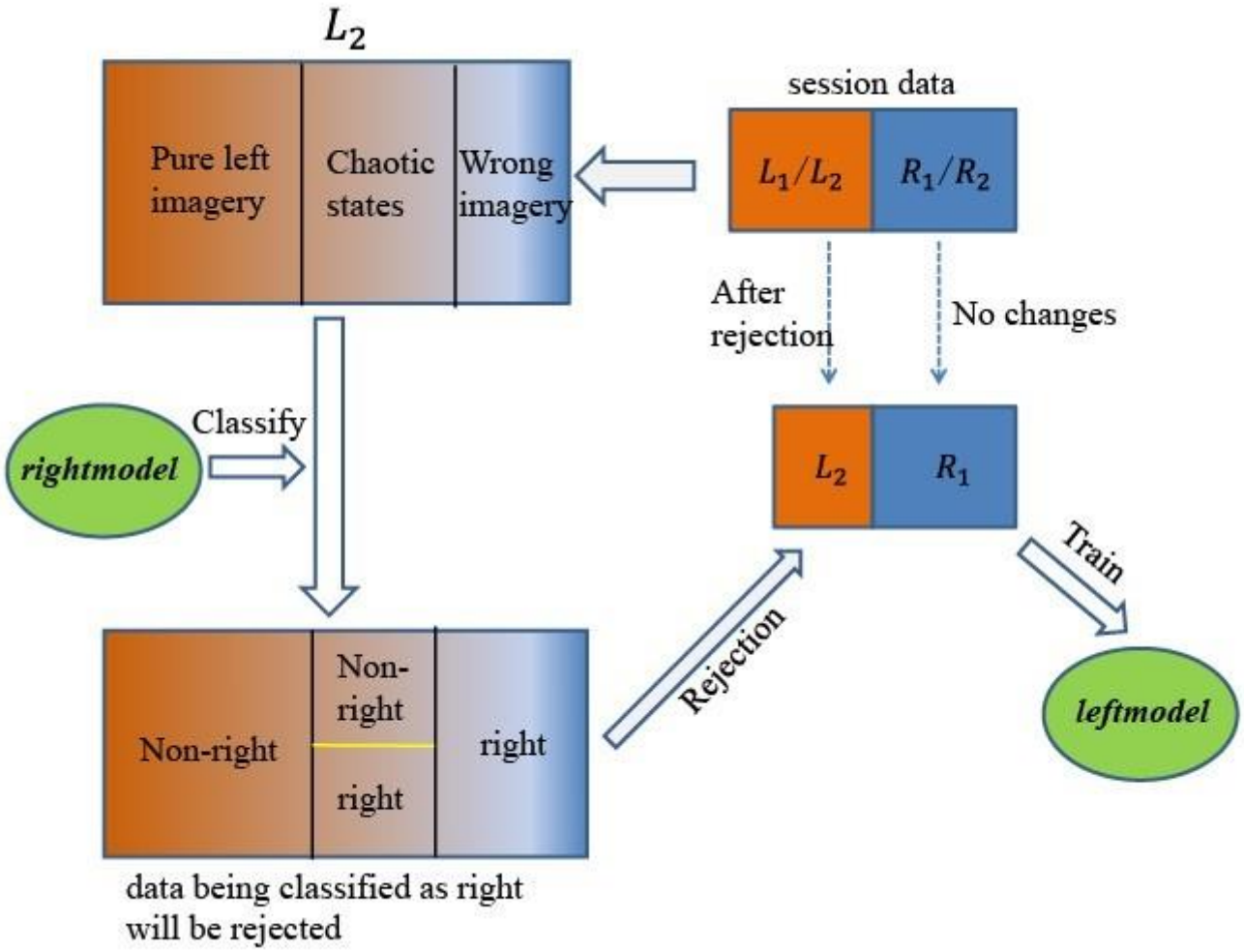
- Example(Left ones)



Left motor imagery

Iterative CSP

- Iteration process



Iterative CSP

Results

1. Improve the classification accuracy for almost

10% compared to general CSP;

2. In most cases, the iteration will converge, maintaining a relatively pure subset.

Problems

1. Very sensitive to the original dataset(initialization);

2. Depend on a **LARGE** scale of EEG data for iteration.

Iterative CSP

Mechanism

1. Better than general CSP, which means our hypothesis about patients' data is partly true;

2. There exist un-concentrated imagery in the datasets;

3. There exist not only single-class(L/R) motor imagery data but also irregular patterns. These irregular patterns may be leaded by injuries on the brain areas, which are hard to deal with by general feature extraction methods and classifiers.

GMM Filter

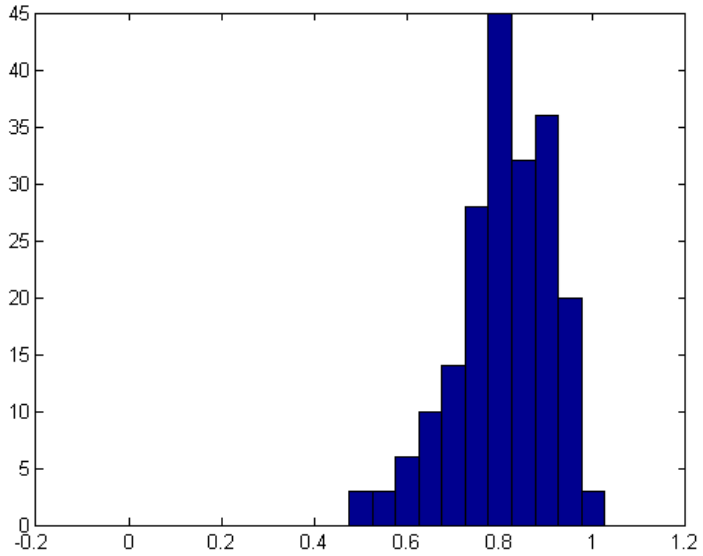
Motivation

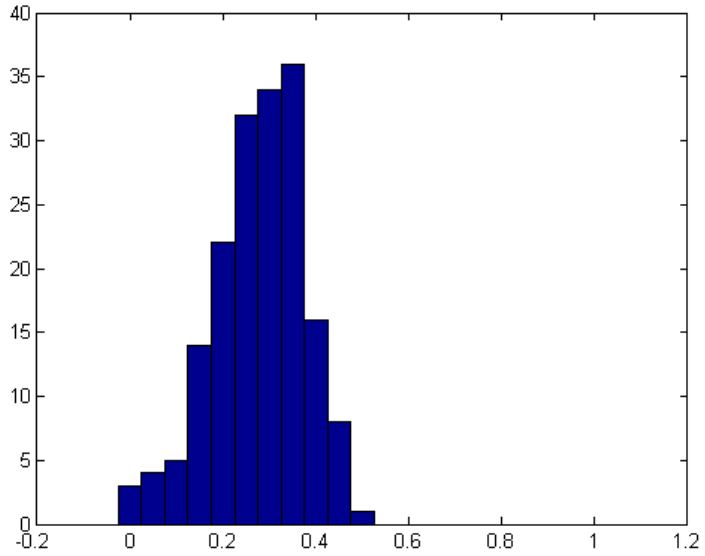
Consider CSP feature $F = (f_1, f_2, f_3, f_4)$.

Generally, f_1, f_4 are the most discriminative ones for classification.

We try to plot f_1 in 2D surface so that we can compare the features between patients' and normal people'.

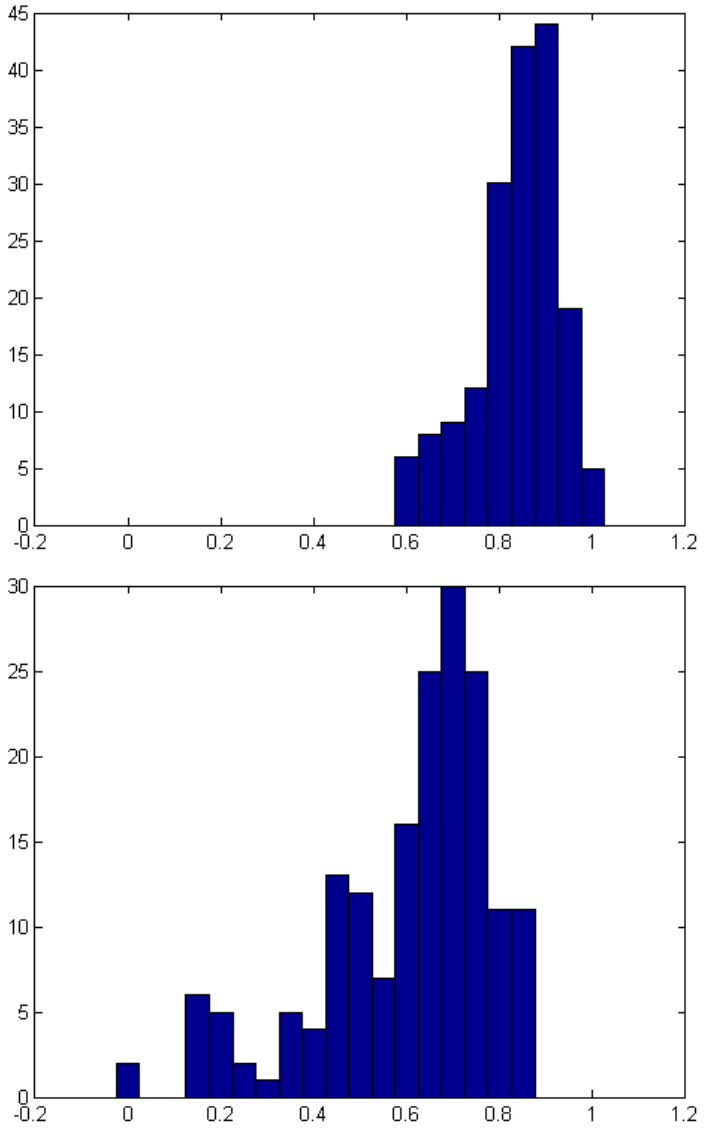
GMM Filter





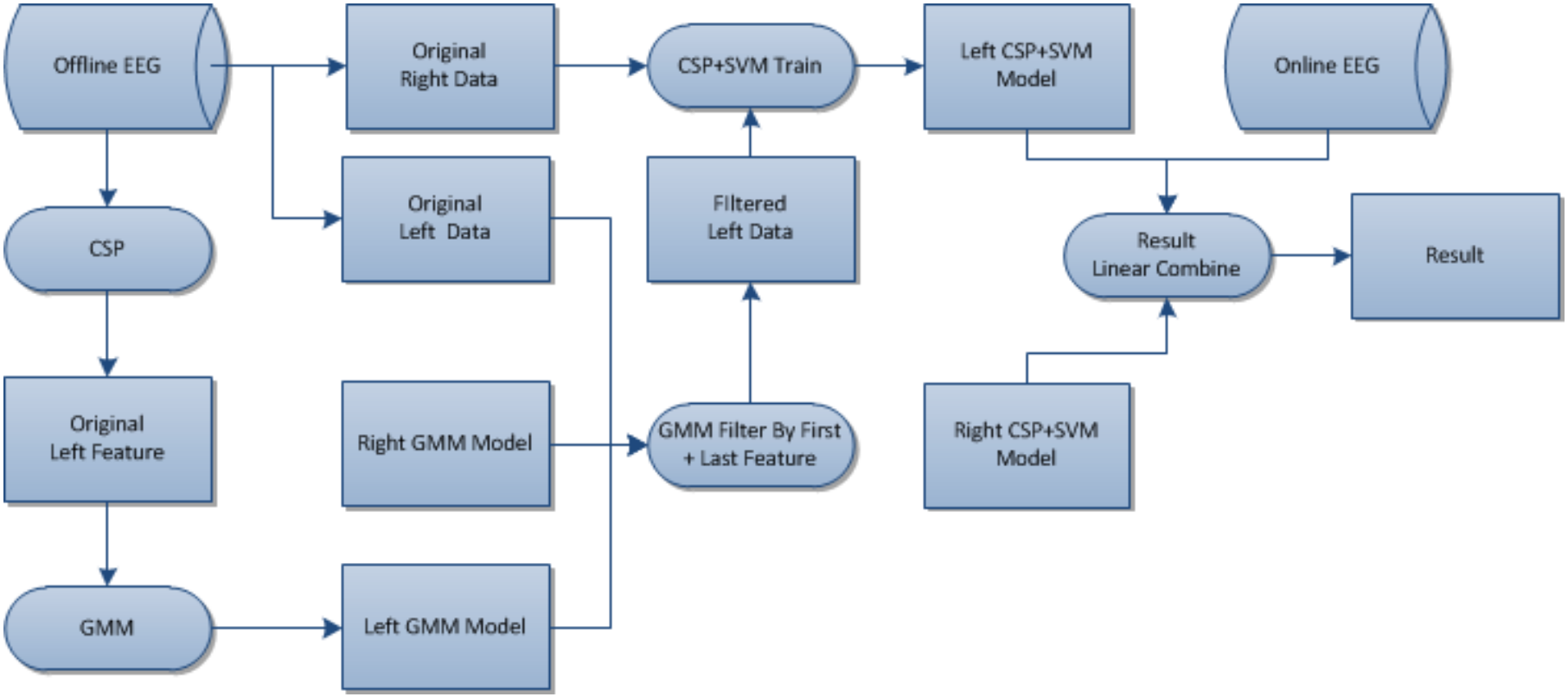
- We can distinguish two kinds of motor imagery by naked eye in this feature;
  - They are quite similar to Gaussian distribution.

GMM Filter



- Overlapping between two classes;
- In general, any single-class feature is Gaussian;
- There may be more than one center: mixture Gaussian.

GMM Filter


Offline EEG
Original Right Data
CSP+SVM Train
Left CSP+SVM Model
Online EEG
CSP
Original Left Data
Filtered Left Data
Result Linear Combine
Result
Original Left Feature
Right GMM Model
GMM Filter By First + Last Feature
Right CSP+SVM Model
GMM
Left GMM Model

GMM Filter

- **Results**

Improve the classification accuracy for almost 10% compared to general CSP;

Problems

1. Dimension Curse: The distribution of the CSP features is very concentrated, sometimes GMM cannot fit the high-dimension features very well.

2. In our experiment, GMM is used as a filter but not a classifier.

GMM Filter

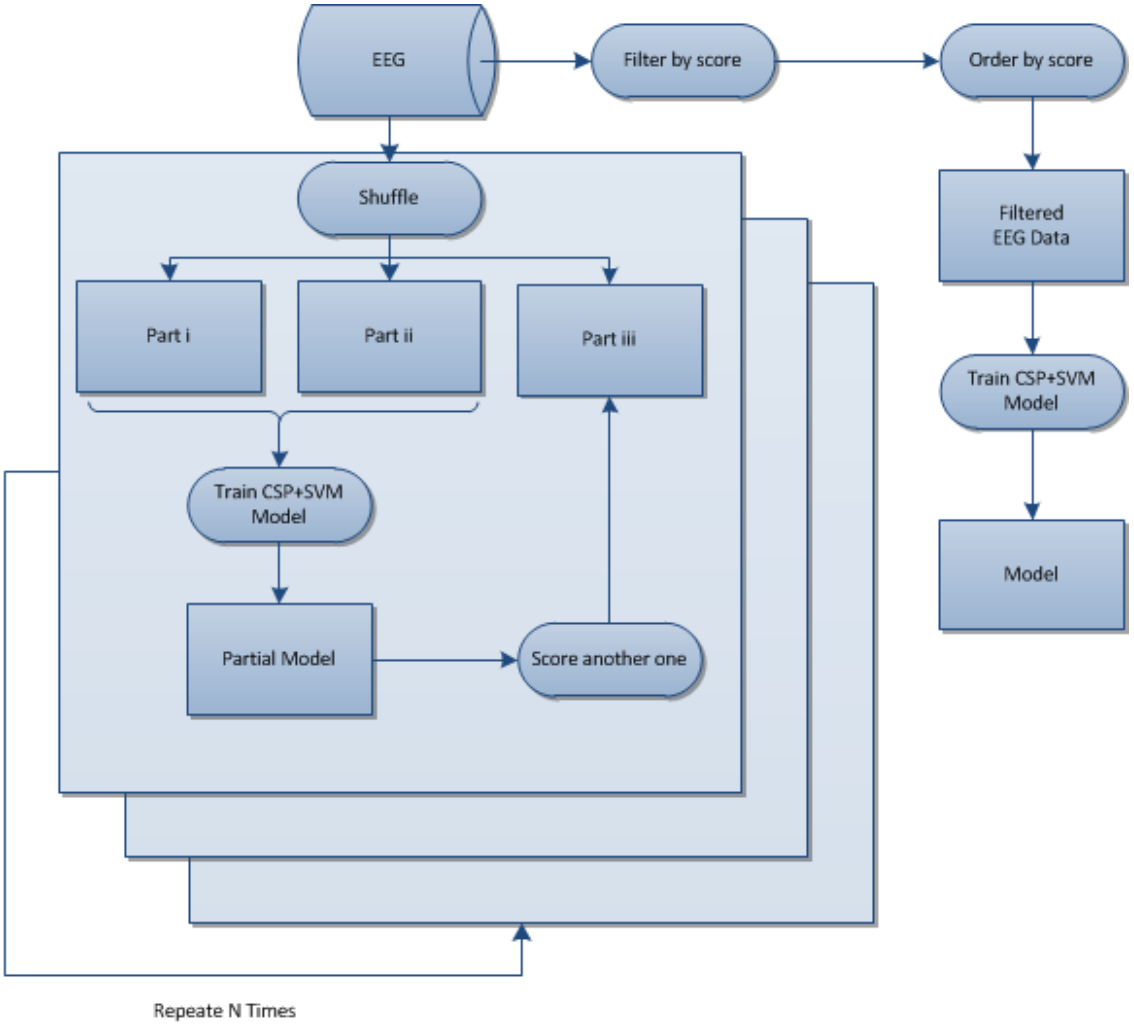
- **Mechanism**

1. The distribution of normal people's features is Gaussian. Naturally, we suppose that of patients is GMM.

2. Overlapping between left and right motor imagery features compared to normal ones.

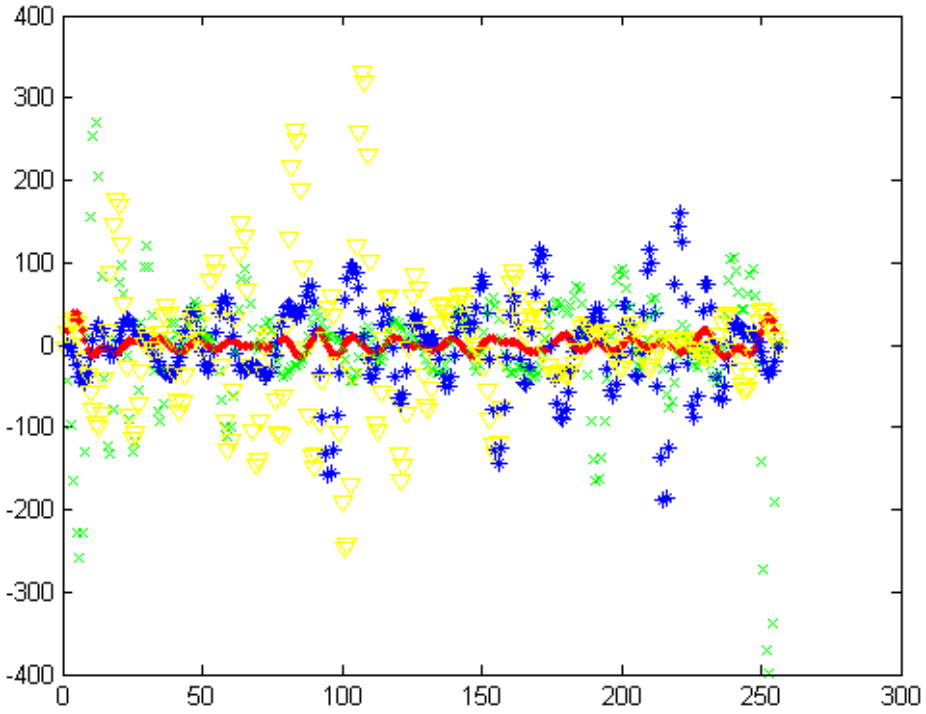
3. More than 2 kinds of imagery patterns.(Sure)

Re-Score



- We hope to find noise by scoring every window data;
- After that, we can handle low-score data by boosting.

Re-Score



- 10 cycles for scoring
- Yellow(10) Green(7) Blue(4) Red(1)
- overfit the high rhythm signals.

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Mixed Dataset Test

Motivation

Original assumptions: Different sessions of EEG share a common motor imagery pattern in a specific day.

Actual situation: The training accuracy is much higher than the testing accuracy. But when exchanging the training and test datasets, we find that sometimes the testing accuracy increases.

New assumptions: There exist major pattern and secondary pattern in a single-class motor imagery.

Test: Mix the EEG windows in trials, we get a more higher testing accuracy in a probability more than 0.7.

Mixed Dataset Test

Results

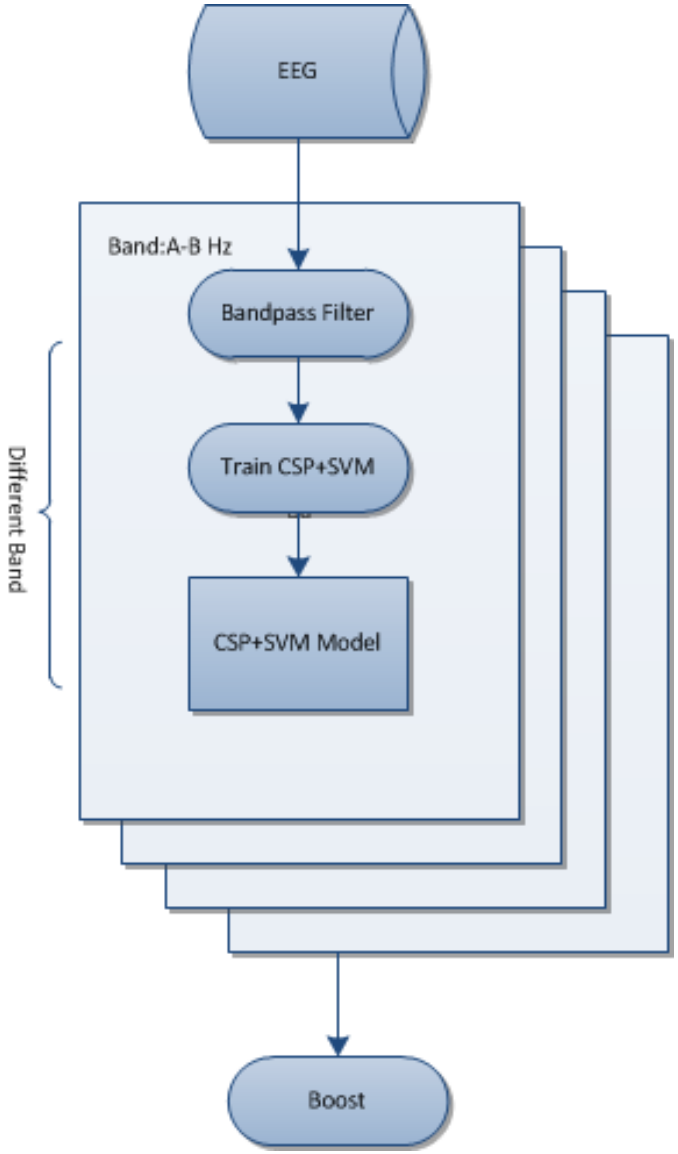
Sometimes we can get a very high testing accuracy.

The mean accuracy maintains between 65% and 75%.

Mechanism

Several imagery patterns intersect in patients' motor imagery. We surmise it is difficult for patients to maintain a fixed motor imagery pattern for a long time(30 mins).

Frequency Boost



- Automotically choose narrow bands for training
- Only use part of the training data to improve generalization capability(2/3).
- Example:

  Step=4 Begin=5 End 39

  L = 6：2：12

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Frequency Boost

Results

1. Improve the classification accuracy in most time compared to general CSP;
2. Boosting prefer higher band such as 20-32Hz;
3. If we add 8-30 Hz as a new band into boosting, sometimes the accuracy will decrease;
4. Boosting will choose different bands when being used in EEG data acquired in different days.

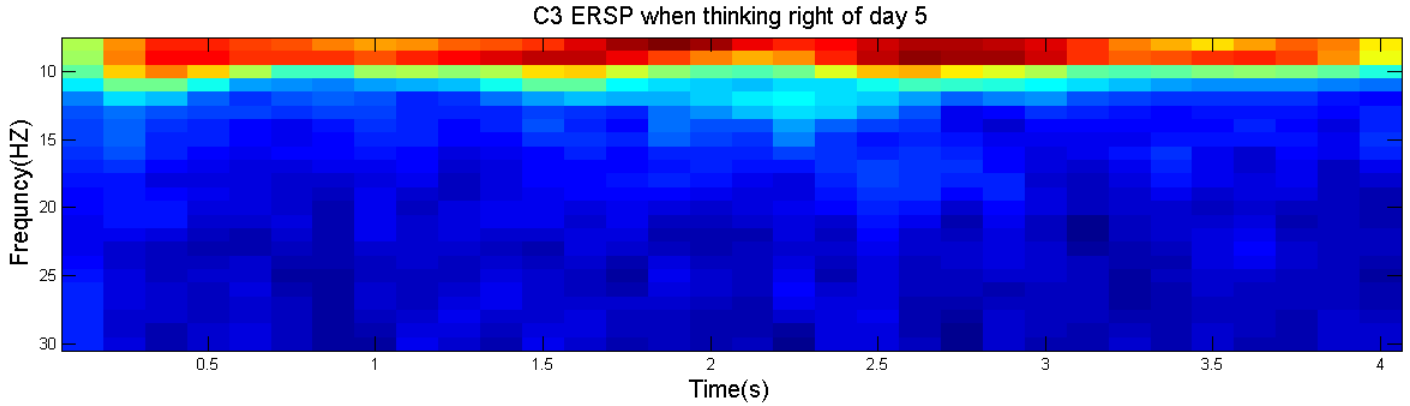
Frequency Boost

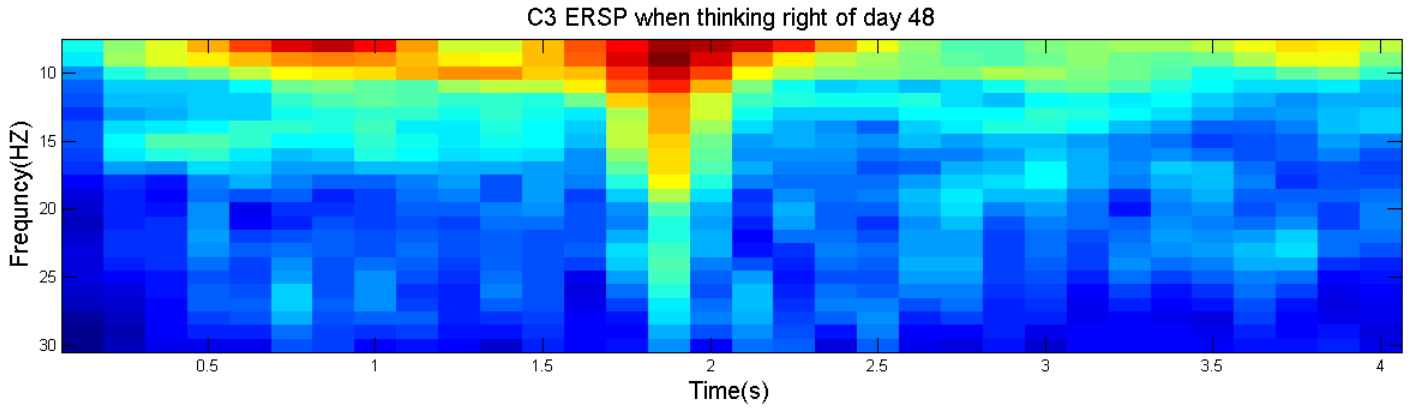
Mechanism

Generally, we filtered the raw EEG data into 8-30 Hz for motor imagery classification.

Compared to normal people, Patients' ERD exists in a much higher band and the band is much narrower.

Frequency Boost





Dynamic Pattern Recognition

- Any model that depends on CSP can not get rid of the variance space. But the variance space cannot represent all of the features of patients' motor imagery EEG;
- Regard the motor imagery as a dynamic process with probability transition;
- Try to build a Language Model for EEG analysis;
- Marcov Chain;
- Conditional Random Field;

Dynamic Pattern Recognition

Problems

We do not have enough data for training a complete probability transition network;

Sparse problems;

We need a applicable smoothing factor.

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Summary

- According to statistical learning theories, 1-NN method can provide the upper bound of the classification accuracy: nearly 80%;
- The motor imagery EEG data of stroke patients are full of dynamic, general static methods cannot extract differentiate features, more pre-processing methods and data-correlated methods are needed;
- There exist hidden-labeled data which we have no priori knowledge about, we need to weaken their impacts;

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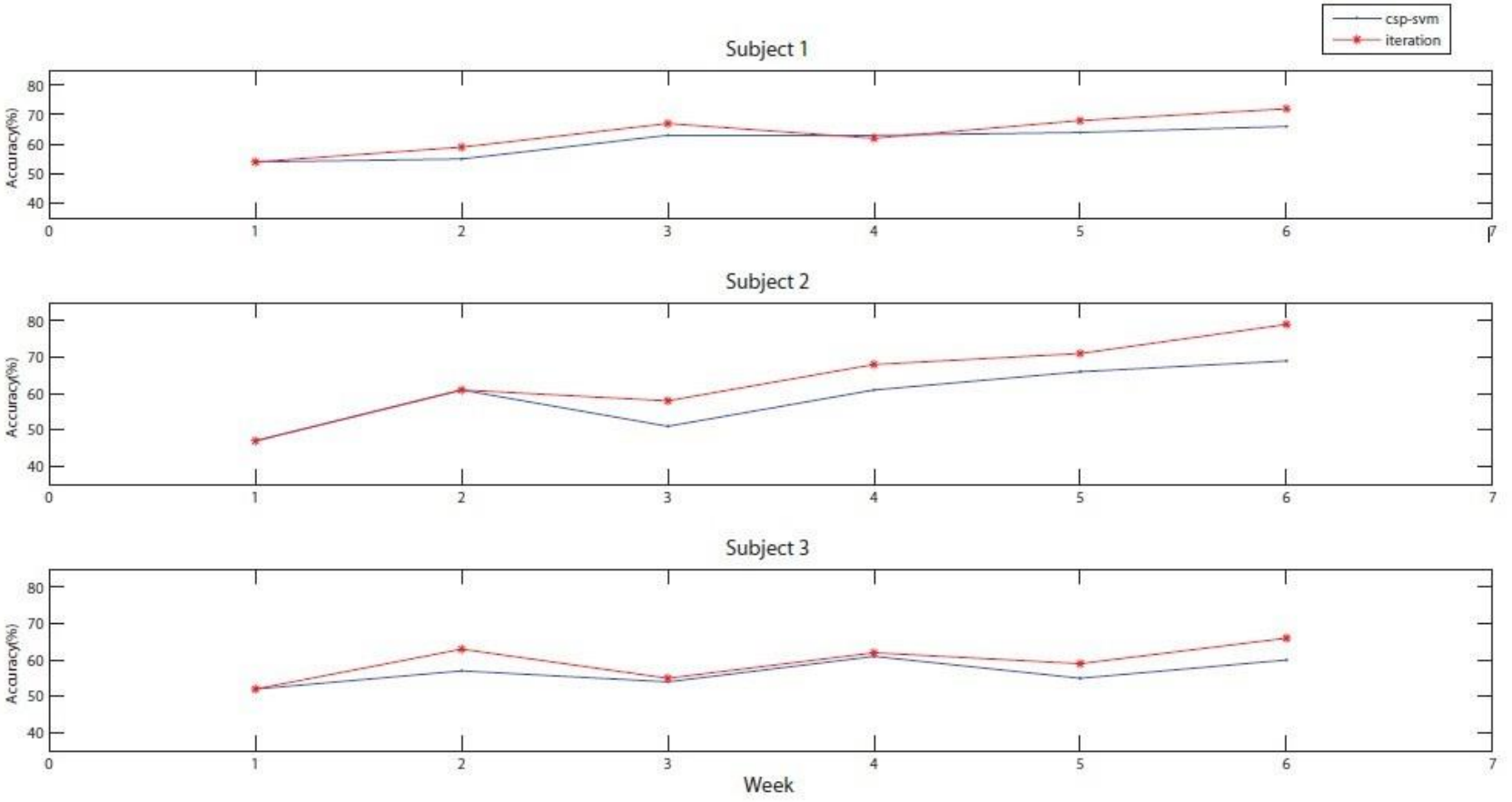
Results

- Seven stroke patients from Zhejiang Taizhou Hospital participate in our study;
- Four of them remain well after 2 months' training while no significant recovery appearances are discovered on the other 3 patients;
- We surmise that these 3 subjects may have missed the best rehabilitation period because all of them have suffered stroke for no less than 8 months;

Subject	Age	Sex	Pathgenesis	1st week	2rd week	4th week	6th week
1	65	female	cortex injury	0.54	0.59	0.62	0.72
2	71	male	basal ganglia injury	0.47	0.61	0.68	0.79
3	62	female	basal ganglia injury	0.52	0.63	0.62	0.66

Results

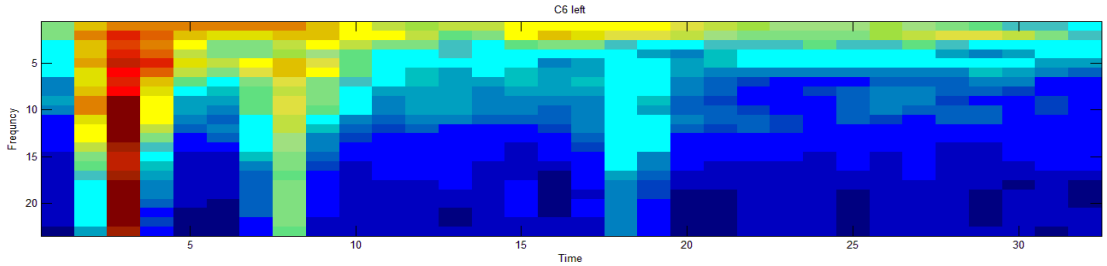

csp-svm
iteration
Subject 1
Subject 2
Subject 3
Accuracy(%)
Week

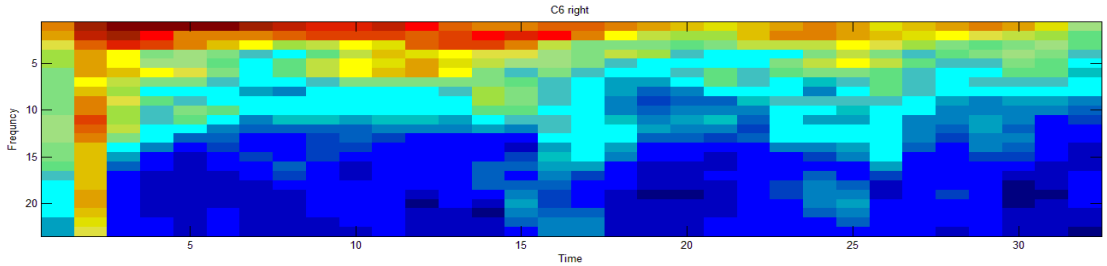
Mechanism Analysis

- Brain Reconstruction Neurophysiologic Mechanism
  - A shift in cortical organization of the affected limb from the ipsilateral hemisphere to the contralateral hemisphere after trained in our system for a period.
- Method
  - Plot each patient's ERSP for each channel of every day.
- Result
  - ERD phenomenon occurs in the unaffected hemisphere no matter imaging left or right, while ERD phenomenon barely occurs in the affected hemisphere.

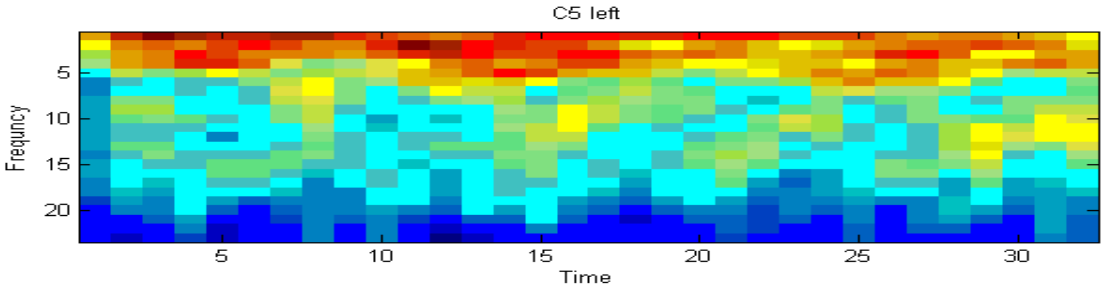
ERSP

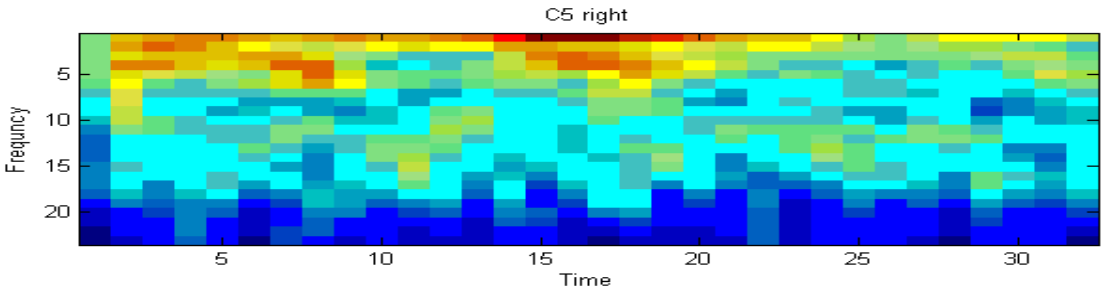
- **Averaged Data**





unaffected hemisphere





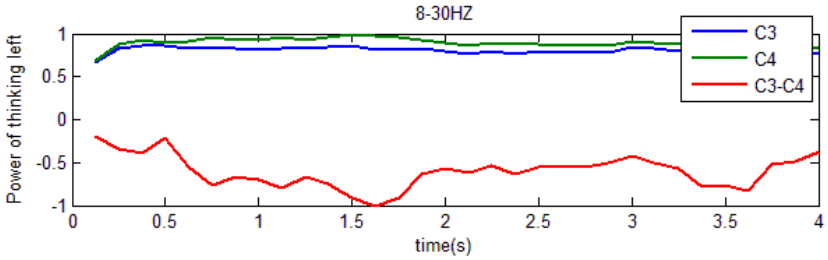
affected hemisphere

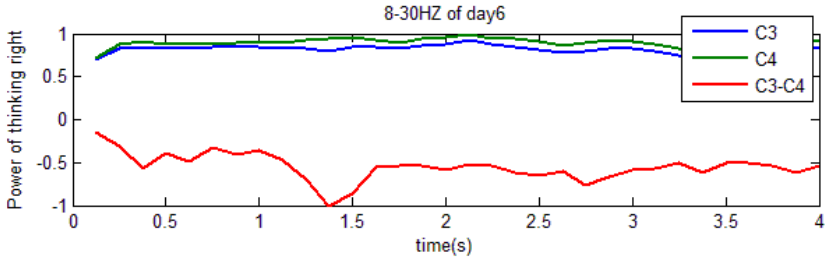
Mechanism Analysis

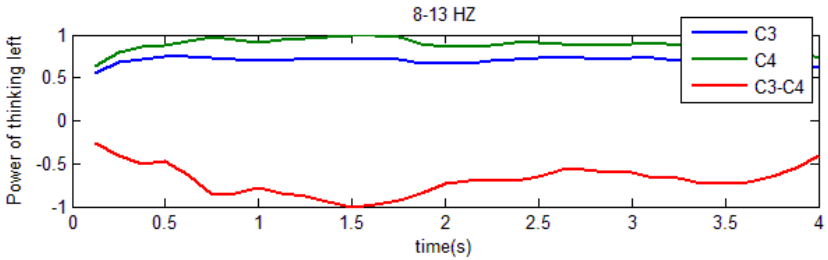
- Brain Reconstruction Neurophysiologic Mechanism
  - massive cortical reorganization reflects either an increase in the excitability of neurons already involved in the affected hemisphere , thus power of affected hemisphere is higher than that of unaffected hemisphere.
- Method
  - Plot each patient’s power spectrum of affected and unaffected hemisphere of every day.
- Result
  - All of the patients participated actively in our experiment, statistics result shows that power of affected hemisphere is higher than that of unaffected hemisphere.

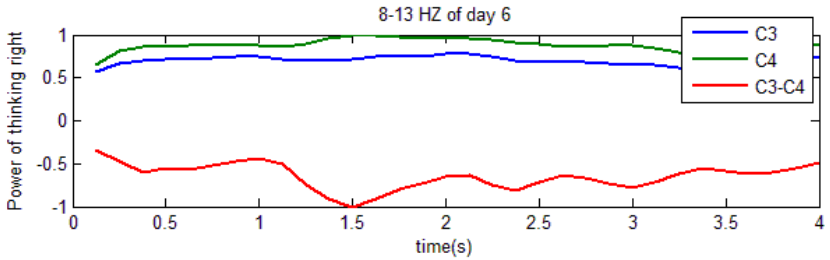
power spectrum

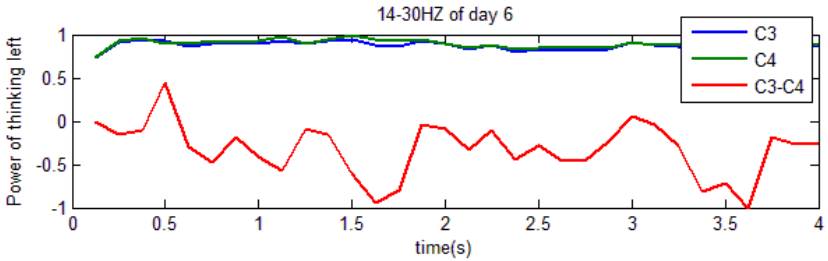
- Averaged Data

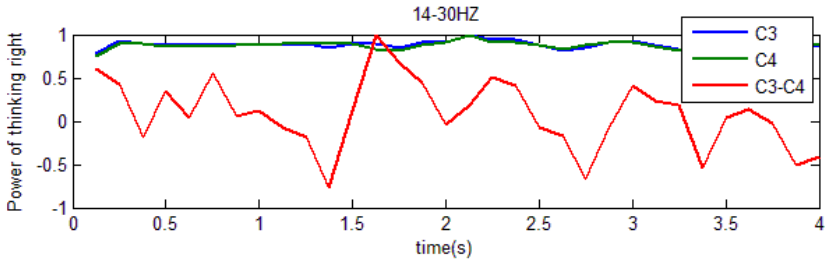










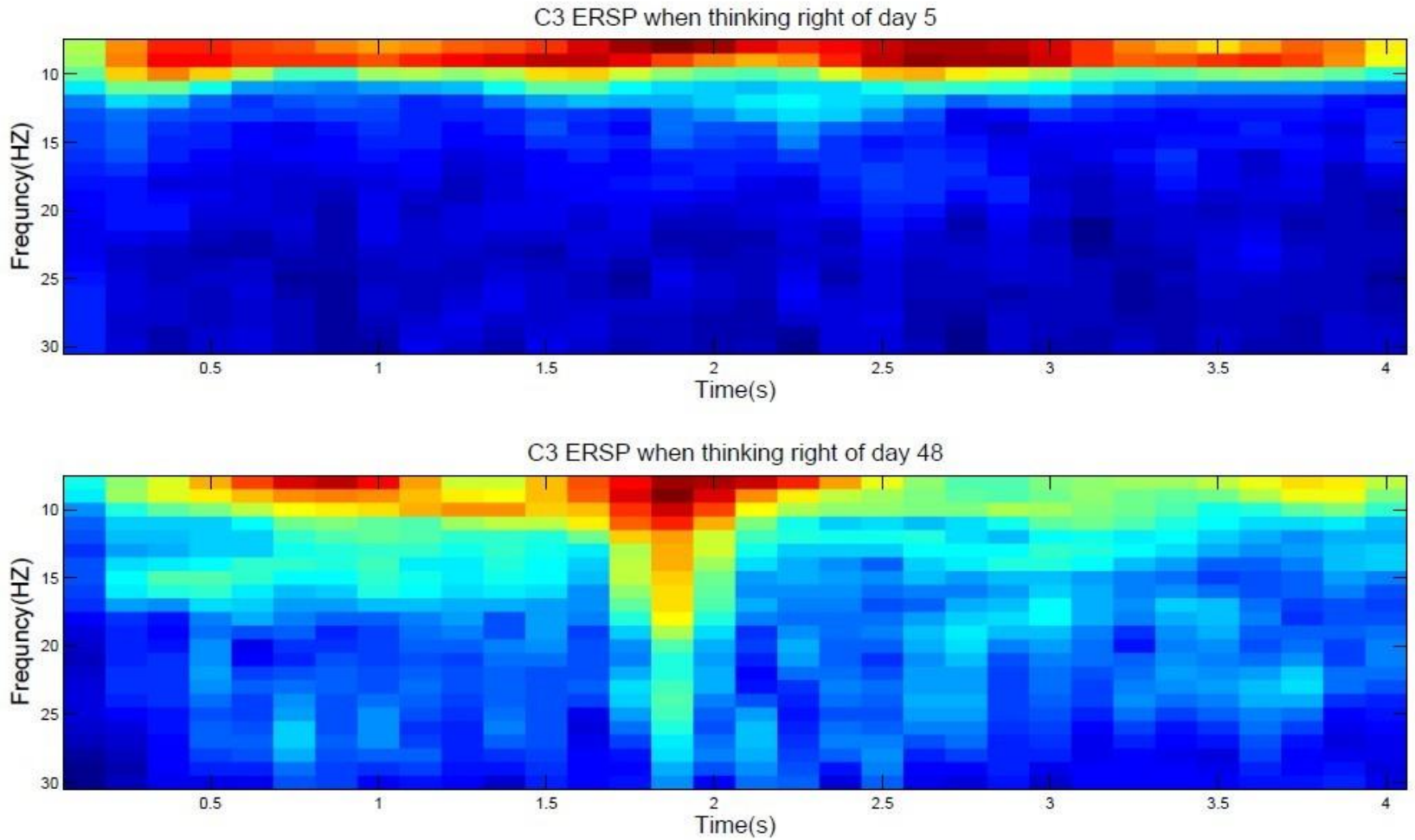


Time-Power figure of different frequency band in affected and unaffected hemisphere, blue line represents the unaffected hemisphere(C3) while green line represents the affected hemisphere (C4)

Rehabilitation effects

- A control group with another 3 stroke patients is observed and recorded during the experiment.
- The group is trained with ordinary medical treatments for 2 months;
- Compared with the experiment group, the clinical rehabilitation parameters of the control group is much lower after post assessment;

ERSP of Day 5 and Day 48



Summary

- ERD
  - Brain reconstruction neurophysiologic mechanism;
  - Unaffected areas will assist affected areas;
- Power
  - More neuron lead to higher power;
  - The power of alpha band(8-13Hz) is higher than beta band(14-30Hz);
- Rehabilitation effects
  - ERD phenomenon appears longer and more obviously after training;
  - The BCI-FES training accelerates the reconstructing of the neuroncircuit of stroke patients;

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Outline

- Background
- Introduction to BCI-FES Rehabilitation System
- Experiment Set-up and Data Acquisition
- Rehabilitation Training
- Data Analysis Methods
- Results and Mechanisms
- Future Work

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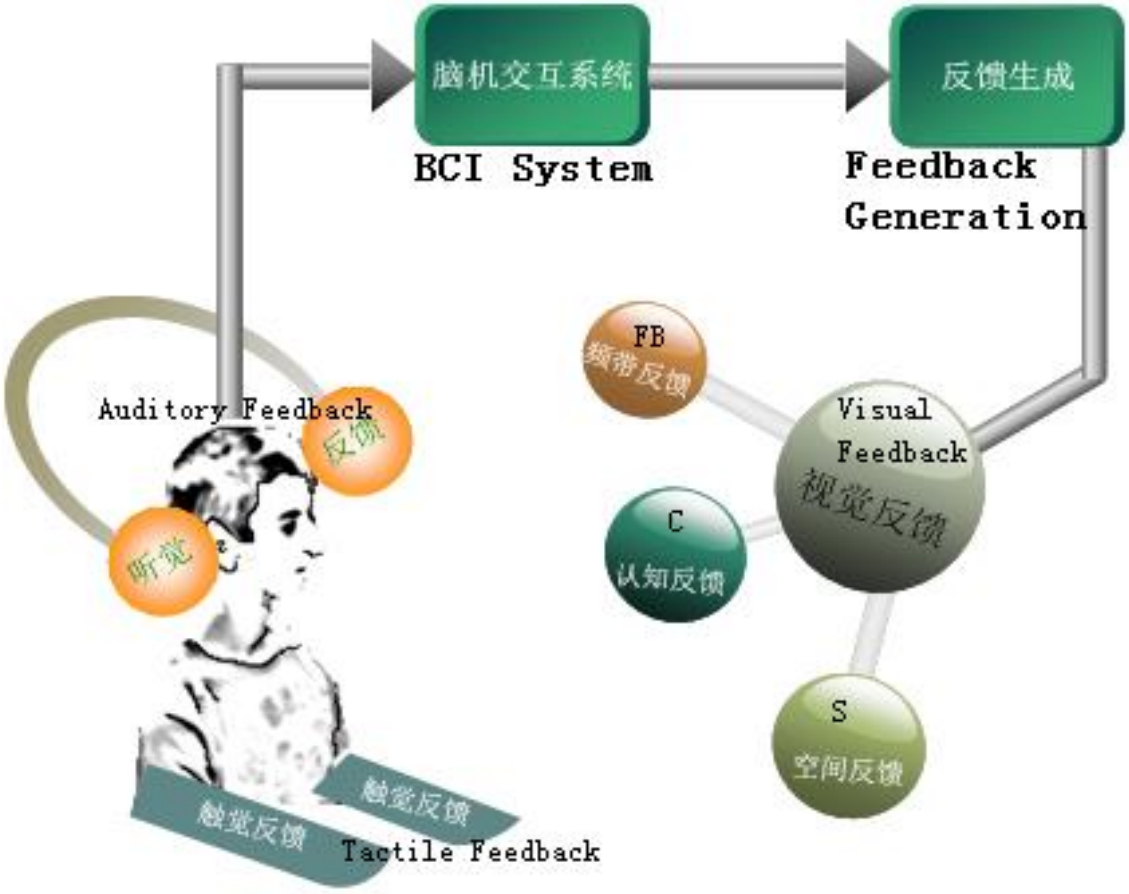
Future Work

- Neurophysiologic Mechanism
  - New Mechanism
  - Motion Imagination / SSVEP / P300 / Affection
- Feature Extraction: Tensor Factorization
  - Noise /Interference
  - Theory/ Fast Algorithms
- Applications
  - Vigilance Estimation
  - Rehabilitation for Motor Function Recovery
  - Multi-user Gaming

Future Work

- Multi-Feedback



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Future Work

- Medical Rehabilitation Issues
  - How to guide subjects to conduct motor imaginary
  - How to train BCI models for Stroke Patients
  - How to give the FES to the patients

Future Work

- More Effective Rehabilitation System
  - Improvement in data acquisition: more detailed tasks
  - The moment for FES stimulation: before or after
- Data Analysis
  - With the help of FMRI
  - More control groups for comparisions
- Rehabilitation Training
  - Competition mechanism with computers
  - Competition mechanism between patients
  - qand help: mechanical arms

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Thank you!