

### **Scripting Prerequisites**



# **Function Calling Syntax**

- Most functions take their arguments in the order in which they are listed in the documentation
- Some can *alternatively* called with all parameters passed in as name-value pairs (using the same names as in the help text, in CamelCase)
- If in doubt, pass them in by name less chance of getting the order wrong, etc.
- It is usually a bad idea to try to mix positional and name-value arguments in one call – don't do it unless that's the default way to call the function

#### • Example:

bci\_train(mydata,myapproach)
bci\_train(`Data',mydata,'Approach',myapproach)



# Loading Data

- A data set (no matter what file format) is loaded using the function io\_loadset()
- It is almost always enough pass in just the file name, as in the example: data = io loadset('/somepath/somefile.xyz')



### **Defining an Approach**



# Defining a new Approach

- Defining an approach is the most complex area in scripting because a data structure must be constructed
- Since an approach is a particular instance of a BCI paradigm (used with custom parameters), an approach definition consists of:
  - The name of the paradigm (e.g., CSP, WindowMeans)
  - Optionally a list of arguments for the paradigm's calibrate() function
- The default way to specify an approach is as a cell array whose first element is the name of the paradigm and whose remaining elements are arguments to its calibrate() function

#### • Example:

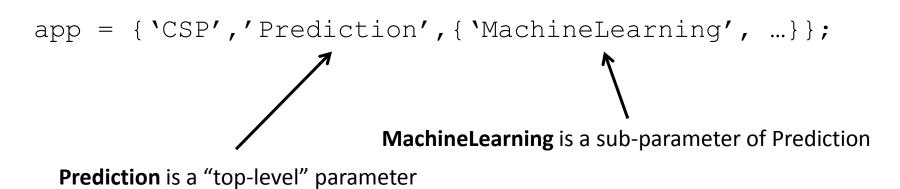
appr = { `CSP', `SignalProcessing',..., `FeatureExtraction',...};



### **Approach Parameters**

- The parameters are a list of name-value pairs
- Important: The argument of an approach are not passed in a long 'flat' list, but they are organized in a hierarchy, i.e. some parameters have named sub-parameters

#### • Example:





### **Approach Parameters**

- Which parameter names a BCI paradigm exposes is the business of the BCI paradigm
- However, practically all of them adhere to a uniform scheme of 2 top-level parameter names:
  - SignalProcessing is a top-level parameter that determines the signal processing stages that shall be used
  - Prediction is a top-level parameter that governs how the prediction function is being calibrated or applied



# **Correspondence With The GUI**

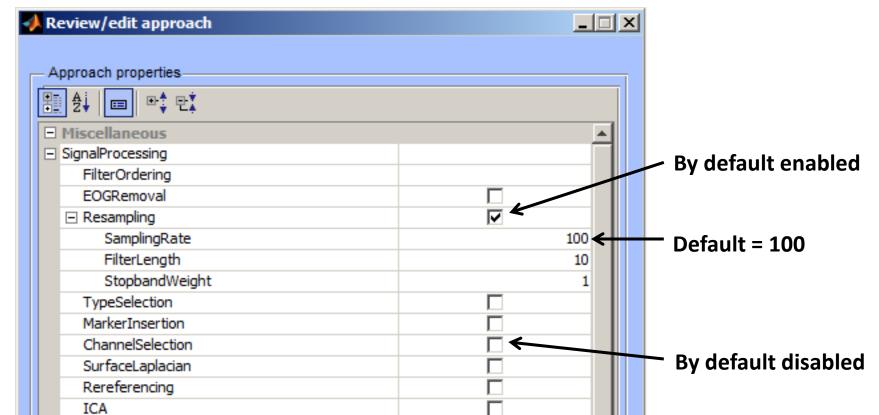
 There is a 1:1 correspondence between the hierarchy of parameters that are specified in scripts and the layout of the parameter tree in the approach definition GUI

	📣 Review/edit approach	
The SignalProcessing parameter	Approach properties	
	E SignalProcessing	
Sub-Parameter	FilterOrdering	
	EOGRemoval	
of Resampling	<ul> <li>Resampling</li> </ul>	
(itself a sub-parameter	→ SamplingRate	100
of SignalProcessing)	FilterLength	10
of Signal Tocessing)	StopbandWeight	1
	TypeSelection	
	MarkerInsertion	
	ChannelSelection	
Sub-parameters of	SurfaceLaplacian	
SignalProcessing	Rereferencing	
5 5	ICA	



### **Default Values**

 Each parameter has a default value (unless it makes absolutely no sense), which can also be looked up in the GUI





### Parameter Help

• Each parameter has a help text, which is also visible in the GUI panel (at the bottom)

	Epochica		
E	Prediction		
	FeatureExtraction		
	TimeWindows	[-0.15 -0.1;-0.1 -0.05;-0.0	
	<ul> <li>MachineLearning</li> </ul>		
	Learner	lda	
	Lambda	0	
	Regularizer	auto	
	WeightedBias		
	WeightedCov		Help text for the
	ConfigLayout	SignalProcessing.Resampling.	selected parameter
T y Au	egularizer pe of regularization. Regularizes the robustness / fluto is analytical covariance shrinkage, shrinkage is sh ad independence is feature independence, also select Help	rinkage as selected via plambda,	Sciected parameter



# The SignalProcessing Parameter

- Has one named sub-parameter for every signal processing plugin that can be used (these are found automatically)
- The name under which a given signal processing plugin appears is up to the plugin – they declare this property at the beginning of their code (you can look it up there)

```
92
         % See also:
 93
              firpm, filter
         웊
 94
         웊
 95
         웊
                                               Christian Ke
 96
         - 😤
                                               2010-04-17
 97
 98
         if ~exp beginfun('filter') return; end
 99
         declare properties ('name', 'FIRFilter', 'folle
100
101
```

Name of the sub-parameter as which this plugin shows up in the approach definition (below SignalProcessing)



# The SignalProcessing Parameter

- The plugins that are listed under SignalProcessing are those in the directories:
  - code/filters (file names beginning with flt\_)
  - code/dataset\_editing (file names beginning with set\_)
- The value assigned to a sub-parameter (e.g., FIRFilter) that is presented by a function (e.g., flt\_fir.m) is by default a cell array of arguments to that function
- The arguments can be passed in any format accepted by the function, but preferably they should again be passed as name-value pairs to avoid confusion



# Configuring Signal Processing Stages

#### • Example:

app={ `CSP','SignalProcessing', ...
 { `FIRFilter', { `Frequencies', [7 8 14 15] } };

- This example defines a CSP-based approach that uses a particular Frequencies value in its FIR filter
- The FIR filter is now also "enabled" if it was not before



### Disabling Signal Processing Stages

• It is sometimes useful to disable a parameter that is enabled by default: This can be written (by convention) as follows:

app={ `CSP','SignalProcessing', { `Resampling',[] };

 Note that these are [] brackets – using {} accidentally would still enable the filter, but passes an empty argument list to it!



# Shortcuts for the Impatient

- BCILAB has the unhealthy habit of allowing *short forms for most things* – I recommend to avoid them whenever possible, but it helps recognizing them
- The most salient short-cut form is when a parameter that has sub-parameters is not assigned a cell array of arguments (like it should), but instead directly the value of the first sub-argument
- Example:



# Shortcuts for the Impatient

- BCILAB has the unhealthy habit of allowing *short forms for most things* – I recommend to avoid them whenever possible, but it helps recognizing them
- The most salient short-cut form is when a parameter that has sub-parameters is not assigned a cell array of arguments (like it should), but instead directly the value of the first sub-argument
- Example:

app={ `CSP','SignalProcessing', { `Resampling',200} };

#### • ... is equivalent to:

```
app={ `CSP','SignalProcessing',...
{ `Resampling', { `SamplingRate',200} } };
```



### **Multi-Option Parameters**

- The last kind of parameter that deserves mention are multioption parameters, which consists of a *selection* argument (a string) and for each possible value a different list of subarguments
- An example are the different alternative variants supported by the ICA filter: amica, infomax, etc., all of which have algorithm-specific sub-arguments
- Below, the parameter named Variant is set to 'fastica', and the MaxIterations sub-parameter of Variant for the *fastica case* is

set to 1000

<ul> <li>SurfaceLapiacian</li> </ul>	
NeighbourCount	8
Rereferencing	
ICA	
Variant	fastica
MaxIterations	1,000
Approach	symm
NumICs	
Nonlinearity	tanh



### **Multi-Option Parameters**

- In scripts, multi-option parameters are written just like the overall approach definition: as a cell array whose first element is the name of the selection followed by name-value pairs for this case
- Example:

..., 'Variant', { 'fastica', 'MaxIterations', 1000, 'Approach', 'symm' }

• ... is equivalent to setting what is shown here in the GUI:

🖃 SurtaceLapiacian				
NeighbourCount	8			
Rereferencing				
⊡ ICA				
Variant	fastica			
MaxIterations	1,000			
Approach	symm			
NumICs				
Nonlinearity	tanh			



### **Other Paradigm Parameters**

- The other parameters behave in exactly the same ways
- Example:
  - MachineLearning is a sub-parameter of Prediction, it has a Learner sub-parameter
  - Learner is a multi-option parameter with one case for each machine learning plugin (e.g., 'lda', 'qda', 'logreg', ...)
  - The sub-parameters of the respective case are those that are exposed by the respective plugin function (e.g., ml\_trainqda.m)



# Configuring the Machine Learning Stage

• Thus, the following is a valid way to configure the machine learning function of a paradigm:

app={ `CSP', 'Prediction', { `MachineLearning', ...
 { `Learner', { `qda' `WeightedBias', true} } };

• It corresponds to the following GUI setting:

qda
auto



# Configuring the Machine Learning Stage

• Thus, the following is a valid way to configure the machine learning function of a paradigm:

app={ `CSP', 'Prediction', { `MachineLearning', ...
 { `Learner', { `qda' `WeightedBias', true} } };

• Alternative shortcut form:

```
app={`CSP', 'Prediction', {`MachineLearning', ...
{`Learner', `qda'}};
Instead of at least {'qda'}
```



### Remaining Script Workflows



# Calibrating ("Training") a Model

- A new BCI model is created using a previously loaded data set (the training set) and a previously defined approach
- This is done using the function bci\_train (the equivalent of the "Train new model..." dialog)

#### • Example:

```
raw = io_loadset('imag.set')
app = { 'SpecCSP', ... };
[loss,model,stats] = bci_train('Data',raw,'Approach',app, ...
'TargetMarkers',{ 'S 1','S 2'});
```



# Calibrating a Model

- The bci\_train function usually takes 3 inputs:
  - The data (Data parameter)
  - The approach (Approach parameter)
  - The description of how event types map onto class labels (TargetMarkers, same as in the GUI)
- The function returns three outputs:
  - The overall loss estimate (e.g. error rate)
  - The learned model
  - Statistics about the model and training process, including results of a cross-validation



# Visualizing a Model

- Models are visualized using the function bci\_visualize
- Example: bci\_visualize(mymodel)
- This function can take extra arguments that are passed on to the responsible drawing function (but few drawing functions have arguments)



# Applying a Model to Test Data

 For offline application to test data, the function bci\_predict can be used – it applies the BCI model to each trial in the data and calculates loss statistics

#### • Example:

```
[outputs,loss,stats] = ...
bci_predict(`Data',mydata,'Model',mymodel);
```

• Note: the first output are the model's predictions for each trial in the data



#### Annotating Data with Continuous BCI Outputs

 The BCI output can be attached as an extra channel (or multiple channels, each representing the probability of class k) to a data set, using the function bci\_annotate

#### • Example:

newset = bci\_annotate('Data', mydata, 'Model', mymodel)



# **Reading Real-Time Data**

 Real-time data can be acquired from a device and written into a named workspace variable using the online reader plugins (run\_read\* functions)

#### • Examples:

run\_readbiosemi(); # read from a BioSemi device

run\_readdataset('MatlabStream','mystream','Dataset',myset);



# Sending Real-Time Outputs

- The outputs of a BCI model as applied to some stream(s) can be calculated in the background online and passed on to some destination – this is done using the online writer plugins (run\_write\*)
- These functions take usually the name of the model to use and the name(s) of the stream(s) to use

#### • Example:

```
run_writevisualization(`Model','mymodel', ...
'SourceStream','mystream')
```



# Performing Batch Analyses

- Using bci\_batchtrain, a single approach can be efficiently applied to a list of data sets or file names
- Also multiple approaches can be applied to one or more data sets in an automated manner
- Can not just train models but also make predictions and evaluate losses on test data sets

• Example:

```
results = bci_batchtrain('Data',mydatasets, ...
'Approaches',myapproaches,'TargetMarkers',mymarkers);
```



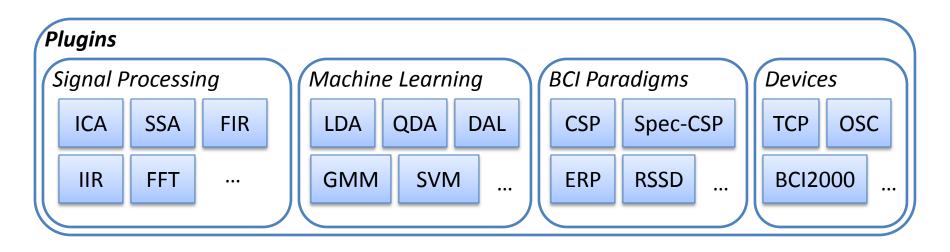
### Parameter Searches

- It is possible to replace (practically) any value in an approach definition by a so-called "search range", i.e. a list of possible values to try automatically in a systematic manner
- A search range is specified by writing the expression search(value1, value2, ..., valueN)
- Multiple search parameters in one approach lead to combinatorial grid search (slow!)

• Example:



#### 3 A Close Look at Components



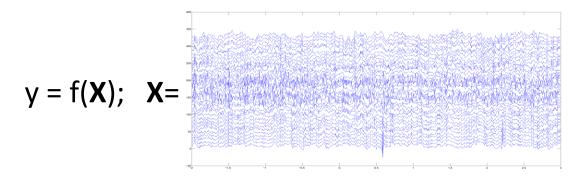


# Component 1: Predictive Mapping



# **Central Predictive Mapping**

• A BCI (with limited memory of the past) can be viewed as a mathematical function *f*:



y= "subj. excited" (+1) "subj. not excited" (-1)

• The functional form is arbitrary, for example

 $y = \operatorname{sign}(\operatorname{var}(WX) + b)$ 

The mapping involves free parameters, here
 W and b, and data from a *sliding window* X



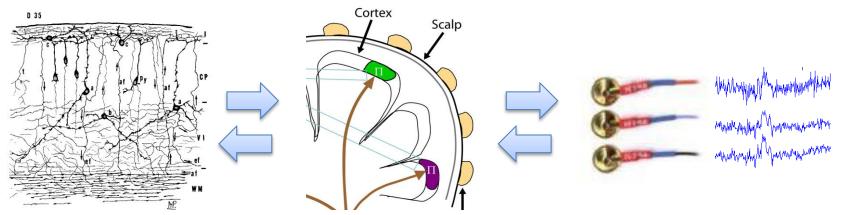
# Choice of a Functional Form

Reflects the relationship between observation (data segment X) and desired output (cognitive state parameter y)



# Choice of a Functional Form

- Reflects the relationship between observation (data segment X) and desired output (cognitive state parameter y)
- Based on some assumed generative mechanism (forward model) – or ad hoc

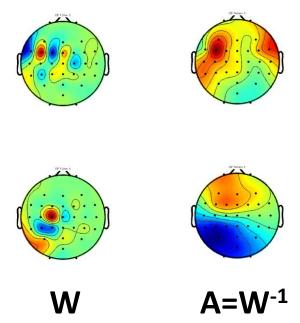


• Remember: Functional form is the inverse mapping!



# Key Ingredient: Spatial Filter

- Linear inverse of volume conduction effect between sources S and channels X
  - X = AS (forward)
  - S = WX (inverse)



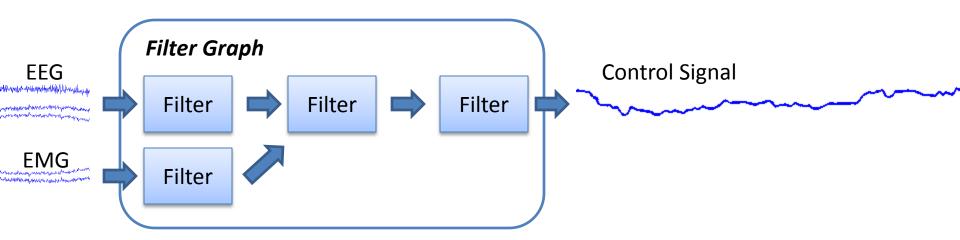


## **Component 2: Signal Processing**



# **Role of Signal Processing**

 BCILAB allows to implemented BCIs using a network of digital signal processing blocks ("filters")

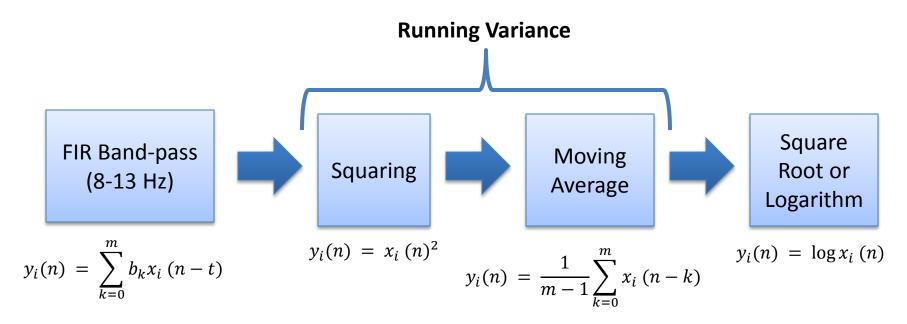


• Relevant filter classes: Spatial Filters, Temporal Filters, Spectral Filters, Spatio-Temporal Filters, Domain Transforms (e.g. DFT)



# **Role of Signal Processing**

 Concrete Toy Example: Feed the amplitude of a brain idle oscillation (e.g. 10 Hz alpha associated with relaxation) from one EEG channel back to the user/subject



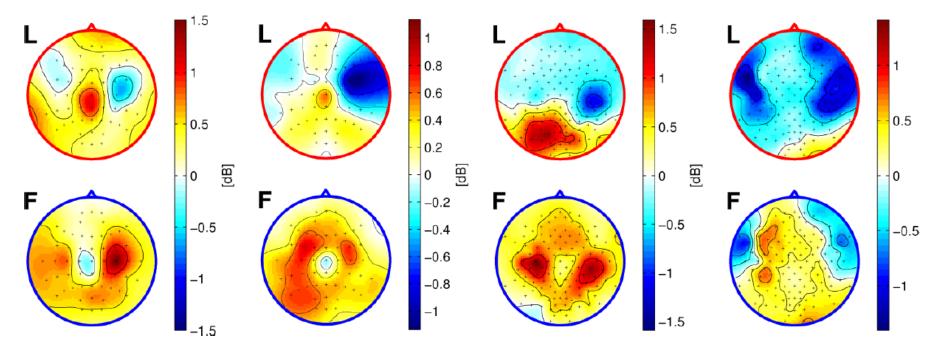


#### **Component 3: Machine Learning**



#### The Problem of Unknown Parameters

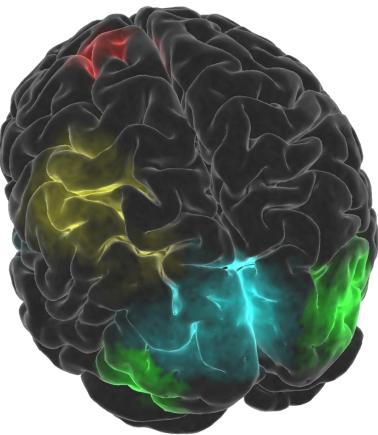
 Processing depends on unknown parameters (person-specific, task-specific, otherwise variable) – e.g., per-sensor weights as below:





#### Reasons for Parameter Uncertainty

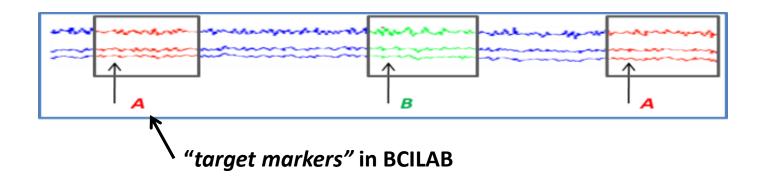
- Folding of cortex differs between any two persons
- Relevant functional map differs across individuals
- Sensor locations differ across recording sessions
- Brain dynamics are nonstationary at all time scales





# **Calibration Data**

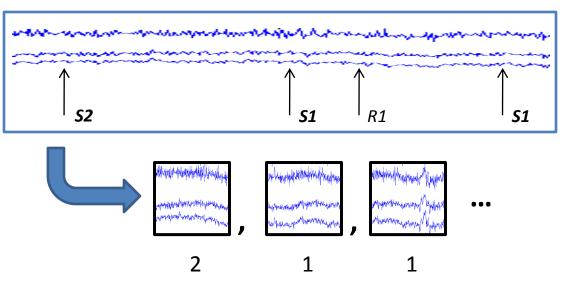
- Many possible kinds of data could be used
- Best known type of calibration data: *example data*, i.e. examples of EEG of a person being excited, not excited, etc.
- Collected in a special *calibration recording* (before actual online use of the BCI)





# Machine Learning In Practice

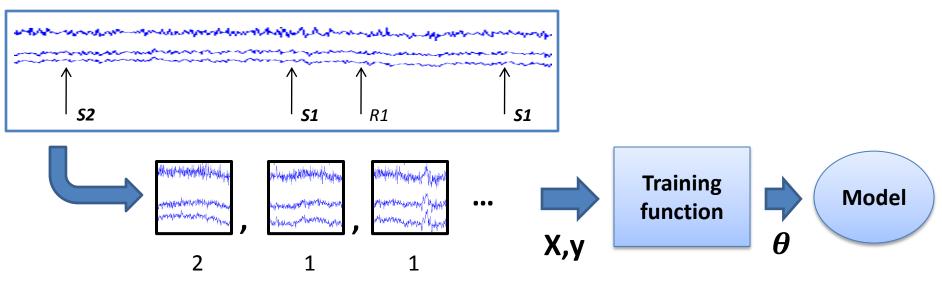
- Often, one trial segment (sample) is extracted for every target marker in the calibration recording and is used as *training exemplar* X<sub>k</sub>
- Its associated label y<sub>k</sub> can be deduced from the target marker





# Machine Learning In Practice

- Often, one trial segment (sample) is extracted for every target marker in the calibration recording and is used as *training exemplar* X<sub>k</sub>
- Its associated label y<sub>k</sub> can be deduced from the target marker





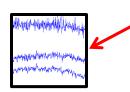
#### **Component 4: Feature Extraction**



## Feature Extraction

- **Caveat:** Off-the-shelf machine learning methods often do *not work very well* when applied to raw signal segments of the calibration recording
  - too high-dimensional (too many parameters to fit)
  - too complex structure to be captured (too much modeling freedom, requires domain-specific assumptions)

1000s of degrees of freedom!





## Feature Extraction

- **Typical Solution**: Introduce additional mapping (called *"feature extraction"*) from raw signal segments onto feature vectors which extracts the *key features* of a raw observation
  - output is usually of lower dimensionality
  - hopefully statistically "better" distributed (easier to handle for machine learning)



## Concrete Example Task

- Flanker Task: The experiment consists of a sequence of ca. 330 trials with inter-trial interval of 2s +/- 1.5s
- At the beginning of each trial, an arrow is presented centrally (pointing either left or right)
- The arrow is flanked by congruent or incongruent "flanker" arrows (preceding the center by a few ms):

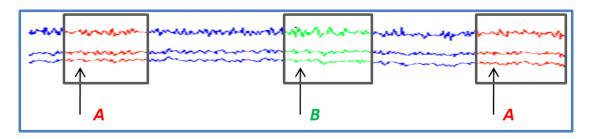
$$\leftarrow \leftarrow \leftarrow \leftarrow$$

• The subject is asked to press the left or right button, according to the central arrow direction, and makes frequent errors (ca. 25%)



# Approach

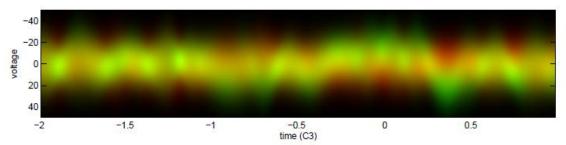
- Calibration recording is band-pass filtered between 0.5Hz and 15Hz
  - 0.5Hz lower edge removes drifts
  - 15Hz upper edge leaves enough room for sharp ERP features
- Epochs are extracted for each trial and label is set to A for incorrect trials and B for corrects

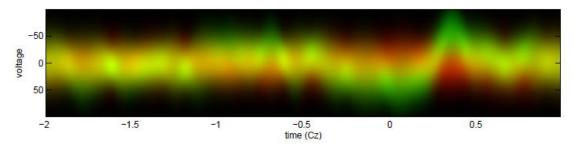


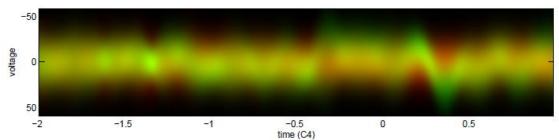


#### Actual Data

 Time courses for all trials super-imposed (color-coded by class) – but here different task

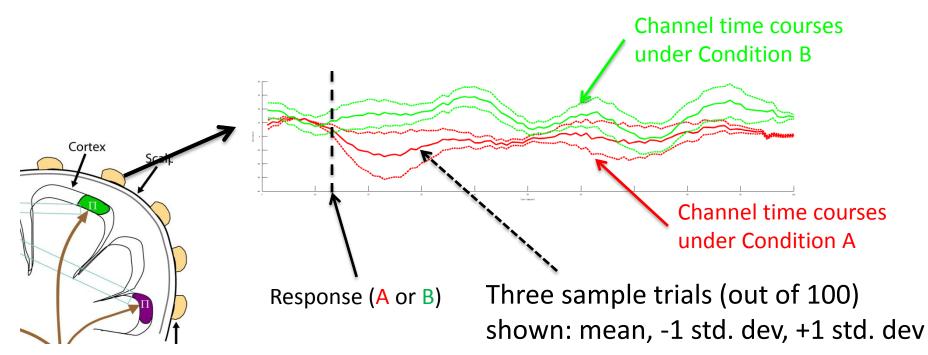






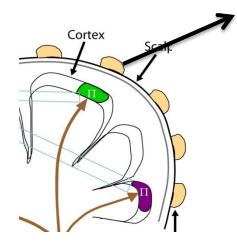


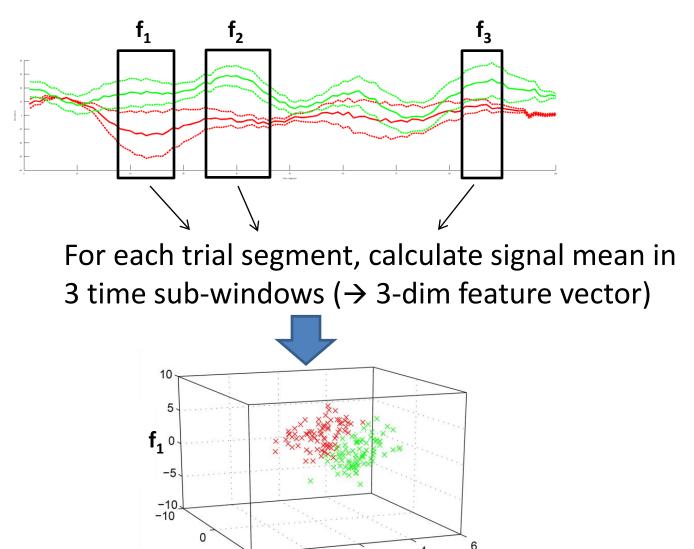
#### **Extracted Epochs**





#### **Extracting Linear Features**





2

0

10

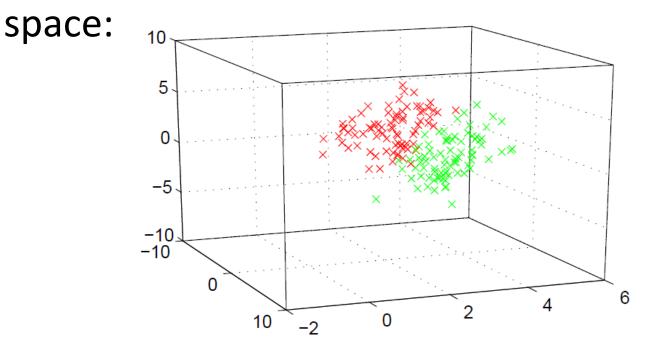
Τ2

-2



## **Resulting Feature Space**

 Plotting the 3-element feature vectors for all error trials in red, and non-error trials in green, we obtain two distributions in a 3d

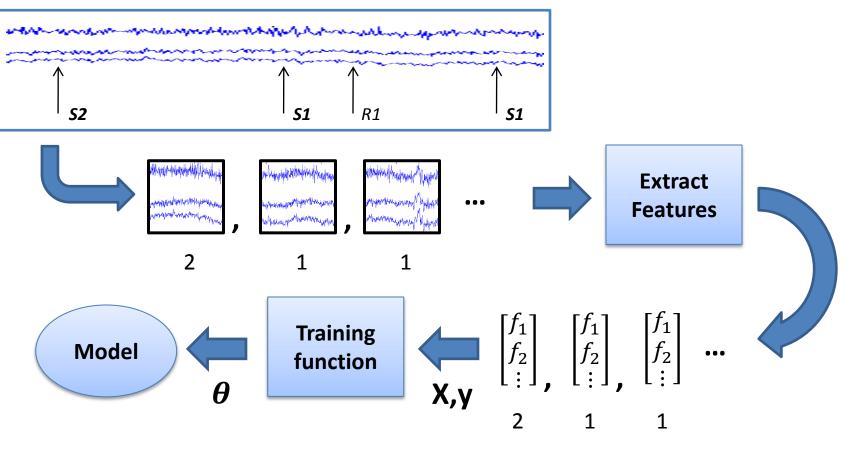


Note that across all channels this space has in fact 3 x #channels dimensions!



## ML with Feature Extraction

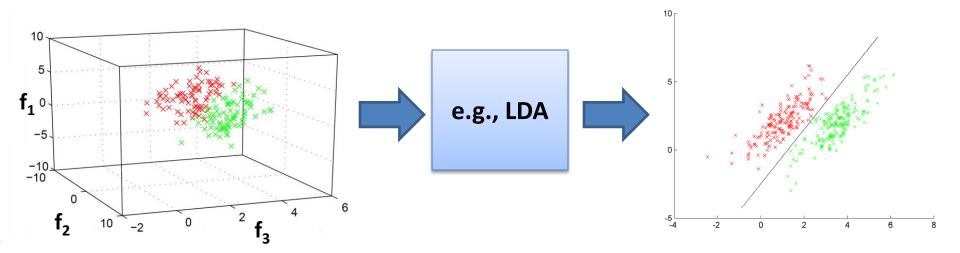
• Including the feature extraction, the analysis process is as follows:





# Machine Learning Continued

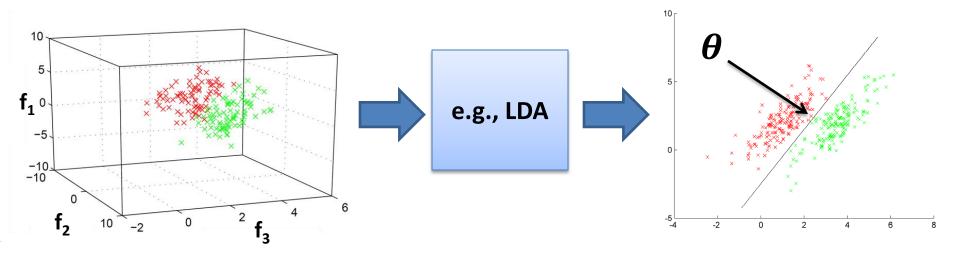
• The feature vectors are passed on to a machine learning function (e.g., Linear Discriminant Analysis)





# Machine Learning Continued

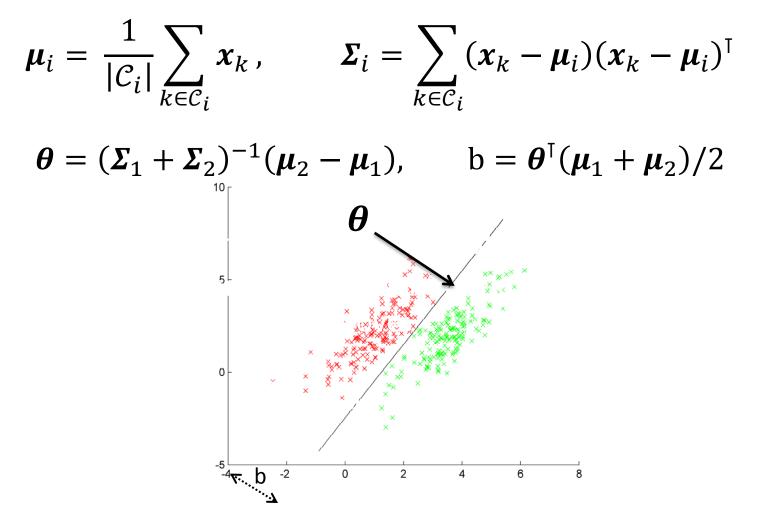
- The feature vectors are passed on to a machine learning function (e.g., Linear Discriminant Analysis)
- ... which determines a parametric predictive mapping





## Simple 2-class LDA In a Nutshell

• Given feature vectors  $x_k$  (in vector form) in  $C_1$  and  $C_2$ ,





# Resulting Predictive Mapping and Model

• LDA produces parameters of a linear mapping

$$y = \theta x - b$$

• For classification, the mapping is actually *non-linear*:

$$y = sign(\theta x - b)$$

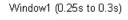
 The learned model with its person-specific parameters here consists of (θ, b); generally it could include adapted signal-processing parameters, feature-extraction parameters, etc.

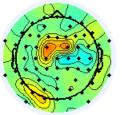


# **Spatial Filters Visualized**

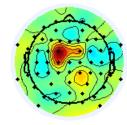
• Topographically mapped, the following filters



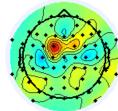




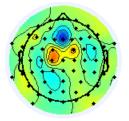
Window2 (0.3s to 0.35s)



Window3 (0.35s to 0.4s)

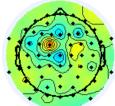


Window4 (0.4s to 0.45s)

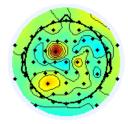


Window5 (0.45s to 0.5s)

Window6 (0.5s to 0.55s)



Window7 (0.55s to 0.6s)



**Note:** This method (and its close relative using "shrinkage LDA" in particular) yield state-of-the-art Performance on ERPs.

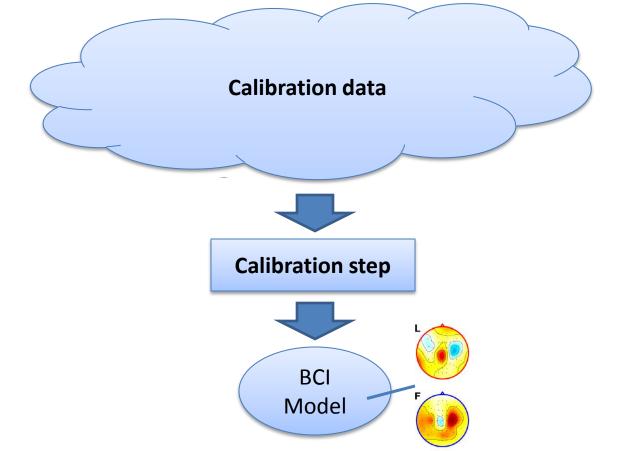


# Even More About Calibration Data



# Model Calibration

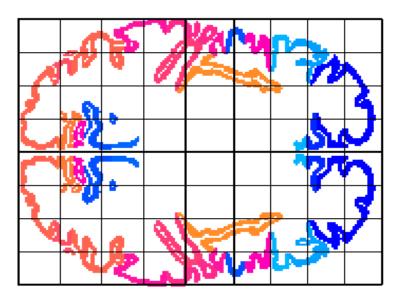
• Can use *calibration / training data* to estimate parameters from, and a separate *calibration step* 





# Prior Knowledge

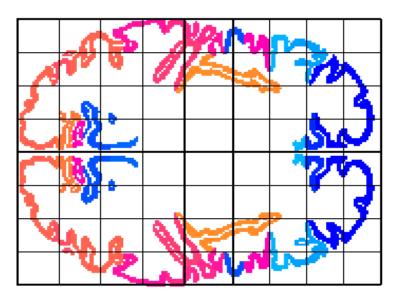
- Prior knowledge is neuroscientific, such as:
  - Anatomical atlases
     (e.g. Talairach, LONI)
  - Functional atlases (if available)





# Prior Knowledge

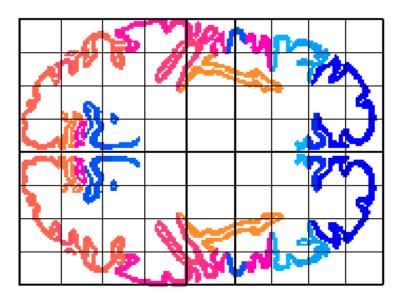
- Prior knowledge is neuroscientific, such as:
  - Anatomical atlases
     (e.g. Talairach, LONI)
  - Functional atlases (if available)
  - Timing information (e.g. neural latencies, reaction times)

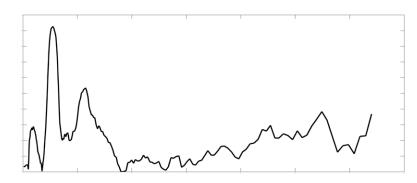




# Prior Knowledge

- Prior knowledge is neuroscientific, such as:
  - Anatomical atlases
     (e.g. Talairach, LONI)
  - Functional atlases (if available)
  - Timing information (e.g. neural latencies, reaction times)
  - Frequency bands of oscillatory processes (alpha, beta, theta, ...)







## **Calibration Data**

• Example/calibration data is used to calculate optimal parameters of a BCI, and is *extremely important* 

En1	www.www.	A. Marada	half wanter harmenter	window when we want	and a surply a surply and as	where a way and a second second	www.parterwert	www.www.www.w	Automation V. L	a sea proving	Martin Martin
Fp1 Fp2 F3 Fz	chemographical and	Annon Aller and	And the season of the season	Active Contraction	education and man	the second s	Mangaran Managaran	wanter warder and	North manual mu	manner	makes and short and an
F3 Fz	- -	Character and a Minister	the second superior	international and the second	and the second	a fan an fritegen fan de fa New de fan de	and the second of the second second	with and a second and the second	and the second second	- marine marine and	were an a company
F4				anter and the second second and the second	and the stand of the second	Microsoft Mark	Stran Constant San San	www.concernante	have have a strange	Mar Marine Marine Marine	www.manutation
FC5 FC3	Farmer A		A start water and a start of the start of th	ALTERNIC ALTERNIC AND ALTERNIC	and the second se	and a second second second second	an water at the part of the	energias-sourcement	A A MOUNTAIN THE AND A MOUNTAIN		
EC1	Server and the server of the	White marchen because the	MAN		and the second		and a second second	and the for th	and which have a start of the	and a second and a second and a second	where and the property
FCz FC2	الانتخاب والمتحم ال	and the second sec	AT THE ACCOUNT OF A PARAMETER	erapparentenenten Angelerantenenten Kanpakardanteko (melaleraturenteneter	month of the second	and the second s	and the second	Warner and the second second	1 Alton and the	the the second second	and a state of the
FC4 FC6	District Antonio and	hundress and a strate attended	M. Dinkster account	brother and the answer and	in an		and a share have been and	monounder and	man man man which	The Contraction of the Contracti	Winter man Avanta
C5	A may marine	MANAGARA AND AND AND AND AND AND AND AND AND AN	and the state of provident	YANG PARTING AND IN AND AND AND AND AND AND AND AND AND AN	<b>᠉</b> ᠃᠉ <b>᠉᠉᠉᠉᠉᠉᠉᠉᠉᠉</b> ᠉᠃᠕᠉᠉᠉᠉᠉᠉᠉᠉᠉᠉᠉	a fan fan strant fan	and the strength of the streng	We are a second to why PAMA	and the low state	while the and the stand of the	UPANAL MARANAL P
C3 C1	and a second		proven the last way we have been	the water and the state of the same	a man all and a second	A CONTRACT OF	an water and a service and the	and a second a second provide	and the manufacture of the second	and the second of the second second second	Contract and the second
Čz		human har all hard	All an and a second a provide a provide a second a provide a second a second a provide a second a se	<sup>a</sup> n an	$\mathcal{T}_{\mathcal{T}}}}}}}}}}$	and a second and a s	and the second and the	veron march was	to Allow how when and	where where the second	manan
C2 C4	and my man	high and when the back that the	when a pring a second	the state of the s	يرأ المحالف بالاهمار العداد	The has a second should be the	with a star an early a second			and an and many have	
C6	Edward manyory	- AND	TYNA A MALADANIA	and the second of second at the second	Collins and Line of the other	We have been and the second	and the second second second	Min Listissen used	March / Barlow And March 1	the lock is a standard and a standard	All Mathematical March 19
CP5 CP3	Carpon many	Banda I I I I I I I I I I I I I I I I I I I	and marken man	were and a service work	alound methodist		Marian with the	mannerhan	www. water water	man and and bail have	monderman
CP1	manne	and the second	and and a second and	Company and a second for the second and the	- and the second and and and and and and and and and a	Mar Mar and a second and a second	- martin	Wa manuna han	and the man when the second	with an and have by south	man mar and all more and
CPz CP2	- manual	and a second and a second with the	when a summer when you								
CP4	and the second	annonementered at 19	The the Arits	hat share the second	2 Property to the state	Weinstein and and the Martin	tion of attack			Man Man Man	
202	F. L. C.	Distant Married Married In 111.	MARK IN THE	A set A some A set a great standard	and new Arest as A	Marine muchiden and	American der & Su 5	in at we then does a	hatter be also when	all whe all the definition of	and the second sec
Pz	a mup routing	KAN AN CALLARD AND AN	and Marine Aparent	water and a wild a wild a wild a wild and	mon and a start	Margare and the second	And a strain of the second of	and the second	A STATES TO A STATE AND A S	A Martin Andrew Martin	and when straide durate
P4 POz	AN CONTRACTOR	L L AND A L L AND A L A		the start and start and start		۲ <sup>-</sup> 4:45 (1) - 4:47		the second have a	Marth and Alle Andrew He	and and the state of the state	The COMPANY COMPANY AND A
01 02		hand a manter provident	man have been where the	proposition of the states of t	we have the property of the pr	Attent for the water of the state of the sta	Kuping Antonian Made Mapon	White Hard Congran Addage A	1 matthe of the strater	and when the shower	warmer water the second
O2 OGh	E	and the second of the									_
OGv	F										-
MGI MGr	È										
			46		47		48		49		
4	0		40		47		40		49		50



- Collected with the same/similar measurement apparatus as used for online runs
  - otherwise extra transformations and uncertainty incurred
- Comprises multiple independent realizations / repetitions / trials (to quantify variability)
  - one-shot learning (one exemplar) is *much* harder



- Collected under conditions that are as close to those of the online runs as possible (i.e., drawn from the same statistical distribution)
  - Same person is preferable
  - Same sensor arrangement is preferable
  - Same session is preferable
  - Task parameters (stress level, ...) should be similar
- Obviously a cost/benefit tradeoff:
  - Would trade off some performance for being able to reuse one recording for multiple sessions and persons



- If there is a systematic bias (e.g., different session), data should cover multiple realizations (e.g., multiple sessions) to capture variability
- A plain EEG recording is "unlabeled" (no knowledge about the association between raw observed signal and the cognitive state variable of interest)
- Labeled data (person is "surprised" / "not surprised") is *far* more useful than unlabeled



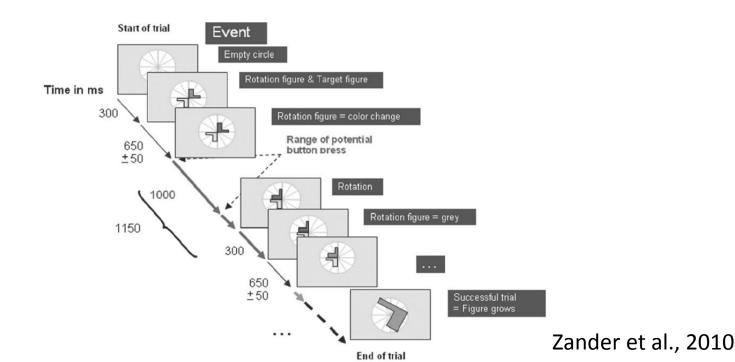
• Labels are assigned per realization (e.g., per trial) and *index the output that the BCI shall produce for this class of data* 

<b>F</b> -4	www. www.	shread white manufacture	an land a general product of the second of the	<del>᠉᠉᠉</del> ᠉᠂ᢞᢠᡕ᠋ᢊᡃ᠇ᡜ᠔ᡃᢊ᠆ᡁᡞᡔᠽᠧ᠆ᠬᢊᢦ᠈᠉ᡔᠿᢪᡟ᠋ᠱᢌᡮᠺᠾᠱᢢᠣᡐ	ᡔᡊᡏᡊ᠊ᡆᠧᡔᡆᡧᢣᠵᢦᡊᠧᡢ᠅ᡧᠺᡘᢛᡗ᠊ᠬᢦᢌᡊᢓᢂᢪᠿᡛᡬᡘᢪᡫᠵᡊᡃᢑᢑᡐᢪ <u>᠋</u>	and and the second an
Fp1 Fp2 F3 Fz	compared when	Marine Constant	and the manual for any other way in a second second	and the advance of the second share and a second	the second second and a second s	A Charles a
F3	Construction and	An and a second s	and the second	a source of the second s	and the second	the stand of the s
Fz	Ь.	March March March				
F4 FC5	anter the second	A CHARLEN AND	Classifield Markensing and Markel Arthonic Markel and Land	waa waa ahaa ahaa ahaa ahaa ahaa ahaa a	and the second	the state the manufacture of the state of th
FC3	a share of		and a second		and the second second at the second se	
FC1	Second and	And an and a state of the second state of the				the second with the second of the second
FCz	provement	and the second	a a server and the se	Mary mary and the second s	and the second	MAnushing and a state of the st
FC2 FC4	-	When and the state of the state	and a set of the set of	and and and the second and the second s	and a state of a state of the second and the state of the	and a second a second a second a
FC6	This parameter	mentaneous Asa arte William Martin and Andrews			Contraction of the second s	The state of the state of the second with the second of the second
C5	amontomical	A WAR ALLAND AND A CARD AND A WAR AND A W	Alter and a share of the second state of the second state of the second state of the second state of the second	Milling a fer and an an an and share a straight a straight a straight	where the new second states been determined to the second states of	Leaven he want of the state of
C3	Freedom	window with the second second	and a second and a	and all marker and and and and a second	angles "he light galanting and a light of the light of the States" in light of the second and the light of the light of States of the second of the light	Manual and the state of the sta
C1 Cz	man	his and have have been and have been and	Merel manufacture and a second a sec	and a second a second a second a	and have an an an a should be an an an	Manute and Manute and a second descention of
C2	and the second	www.www.www.www.www.www.www.www.www.ww	Mar Company and a start and a start and a start a start a start and a start a start a start a start a start a s	the second s		
C1		monder wanter with all the ball of a last day	անությունը» ավերացերաներությունը, որ չուր էր ու ու որ չուր էր ու	the set is the set of	and the second and the second and the second s	Martin Martin and Martin Start Start Martin Martin Start Start
	Estimation alternation of	LAND AND A THE REAL PROPERTY OF	an a	and the second	entranski king nacionalski pana populaci	<b>新闻和小小小小小小小小小小小小小小小小小小小小小小</b>
CP5 CP3	t any many	Mark Mark Mark Mark	Monte Company monte marker that he	in Mithally man how when you we want	when we are an an an an and the way the	month in a stand has a new manus
CP1	Province and		and the second of the second of the second of the second of the	the second s	way to be a man for the stand the marked	Mittan and and the de types have and a she wanted
CPz	Annound	have a have been and a second a	Mary have a second and the second sec			and we have and and a service of the
CP2	<b>ANNO THAN</b>	and a start of the start of the	the short of the state of the s	the second s	many many many transformer and the second states and the second	and the second of the second o
CP4 CP6	which a worked of	KANADA KANADA TATA TATA TATA TATA TATA TATA TATA				
P3	Same and the second	And In Workshows	Mexicondrons & recommendation Austral	un Males much white or Almenter	analter son crime marker on service when when	month show here build with and
P3 Pz	2 min hand hand	the second state of the se	when the man and a wild a man the second and the second	the attalling many work working many	how the second	a short we are a short of the second s
P4	Procession and	ALL PROVIDENCE AND A DESCRIPTION OF A DE	and the second second second second	atter a the second and a star and a second and a second second second second second second second second second		and the second
01	-	a subsective the subsective the subsection of	Alexandratics and American the alteration of	ليتوجلهم فليق والاسالية ومرجع والمتعار والمعار والمعرب والمعالية والالتجام والمعالي	have also where the program of the approximation of the set the set of the set	- the second with making the second second with some sets
01 02	H	Print a Joseph and a second a second a second	and the second	a we can be been been a other or early in the	and the start of a start of a start way a discussion of the start of the start of the start of the start of the	and some all & an ideals denote the second stand
OGh	F					
OGV	F					
MGr	Ę					
	L					
4	5	46	47	48	49	50



#### Summary

 The required data to calibrate a BCI resembles data produced by *controlled psychological experiments*





## Summary

- Features
  - continuous EEG (or other)
  - multiple trials/blocks (capturing variation)
  - randomized (eliminating confounds)
  - event markers to encode cognitive state conditions of interest, e.g., stimuli/responses (called *"target markers"* in BCILAB)
- Can also be used for offline performance tests

and many many hours and the second se						
			$\uparrow$			
<sub>52</sub>	<sub>S1</sub>	R1	S1			



#### A Further Reading



# These and Futher Slides:

ftp://sccn.ucsd.edu/pub/bcilab/



# **BCI Papers Worth Reading**

- B. Blankertz, S. Lemm, M. Treder, S. Haufe, and K.-R. Mueller, "Single-trial analysis and classification of ERP components A tutorial", NeuroImage, vol. 56, no. 2, pp. 814–825, May 2011.
- F. Lotte and C. Guan, "Regularizing common spatial patterns to improve BCI designs: unified theory and new algorithms," IEEE Transactions on Biomedical Engineering, vol. 58, no. 2, pp. 355-362, Feb. 2011.
- R. Tomioka and K.-R. Mueller, A regularized discriminative framework for EEG analysis with application to brain-computer interface", NeuroImage, vol. 49, no. 1, pp. 415–432, 2010.
- B. Blankertz, G. Dornhege, M. Krauledat, K.-R. Mueller, and G. Curio, "The non-invasive Berlin brain-computer interface: Fast acquisition of effective performance in untrained subjects", NeuroImage, vol. 37, no. 2, pp. 539–550, Aug. 2007.
- M. Grosse-Wentrup, C. Liefhold, K. Gramann, and M. Buss, "Beamforming in noninvasive brain-computer interfaces", IEEE Trans. Biomed. Eng., vol. 56, no. 4, pp. 1209–1219, Apr. 2009.



# **BCI Surveys**

- A. Bashashati, M. Fatourechi, R. K. Ward, and G. E. Birch, "A survey of signal processing algorithms in brain-computer interfaces based on electrical brain signals", J. Neural Eng., vol. 4, no. 2, pp. R32–R57, Jun. 2007.
- F. Lotte, M. Congedo, A. Lecuyer, F. Lamarche, and B. Arnaldi, "A review of classification algorithms for EEGbased brain-computer interfaces", J. Neural Eng., vol. 4, no. 2, pp. R1–R13, Jun. 2007.
- S. Makeig, C. Kothe, T. Mullen, N. Bigdely-Shamlo, Z. Zhang, K. Kreutz-Delgado, "Evolving Signal Processing for Brain– Computer Interfaces", Proc. IEEE, vol. 100, pp. 1567-1584, 2012.



# Interesting Technical Papers

- D.P. Wipf and S. Nagarajan, "A Unified Bayesian Framework for MEG/EEG Source Imaging," NeuroImage, vol. 44, no. 3, February 2009.
- S. Haufe, R. Tomioka, and G. Nolte, "Modeling sparse connectivity between underlying brain sources for EEG/MEG," Biomedical Engineering, no. c, pp. 1-10, 2010.
- S. Boyd, N. Parikh, E. Chu, and J. Eckstein, "Distributed Optimization and Statistical Learning via the Alternating Direction Method of Multipliers," Information Systems Journal, vol. 3, no. 1, pp. 1-122, 2010.
- P. Zhao and B. Yu, "On Model Selection Consistency of Lasso," Journal of Machine Learning Research, vol. 7 pp. 2541-2563, 2006.



# Technical Papers, ct'd

- J. Ngiam, A. Khosla, M. Kim, J. Nam, H. Lee, and A. Ng, "Multimodal Deep Learning," in Proceedings of the 28th International Conference on Machine Learning, 2011.
- K. N. Kay, T. Naselaris, R. J. Prenger, and J. L. Gallant, "Identifying natural images from human brain activity," Nature, vol. 452, no. 7185, pp. 352-355, Mar. 2008.
- O. Jensen et al., "Using brain-computer interfaces and brain-state dependent stimulation as tools in cognitive neuroscience," Frontiers in Psychology, vol. 2, p. 100, 2011.
- D.-H. Kim, N. Lu, R. Ma, Y.-S. Kim, R.-H. Kim, S. Wang, J. Wu, S. M. Won, H. Tao, A. Islam, K. J. Yu, T.-I. Kim, R. Chowdhury, M. Ying, L. Xu, M. Li, H.-J. Cung, H. Keum, M. McCormick, P. Liu, Y.-W. Zhang, F. G. Omenetto, Y Huang, T. Coleman, J. A. Rogers, "Epidermal electronics," Science vol. 333, no. 6044, 838-843, 2011.



## Researchers to Watch

- Klaus-Robert Mueller et al. (TU Berlin) one of the leading BCI groups http://www.bbci.de/publications.html
- Marcel van Gerven et al. (Donders) BCI and Neuroscience with a Bayesian approach <u>https://sites.google.com/a/distrep.org/distrep/publications</u>
- Ryota Tomioka (U Tokyo) known for some technical achievements <u>http://www.ibis.t.u-tokyo.ac.jp/RyotaTomioka</u>
- Karl Friston et al. (UC London) working on relevant underpinnings for neuroimaging (outside BCI) <u>http://www.fil.ion.ucl.ac.uk/Research/publications.html</u>
- Leading Statisticians and Machine Learners: Michael I. Jordan, Andrew Ng, Lawrence Carin, Zoubin Ghahramani, Francis Bach, Geoffrey Hinton, Ruslan Salakhutdinov, Yeh Whye Teh, David Blei, ...