Event-related Potentials in Brain-computer interfacing (ERPs in BCI)

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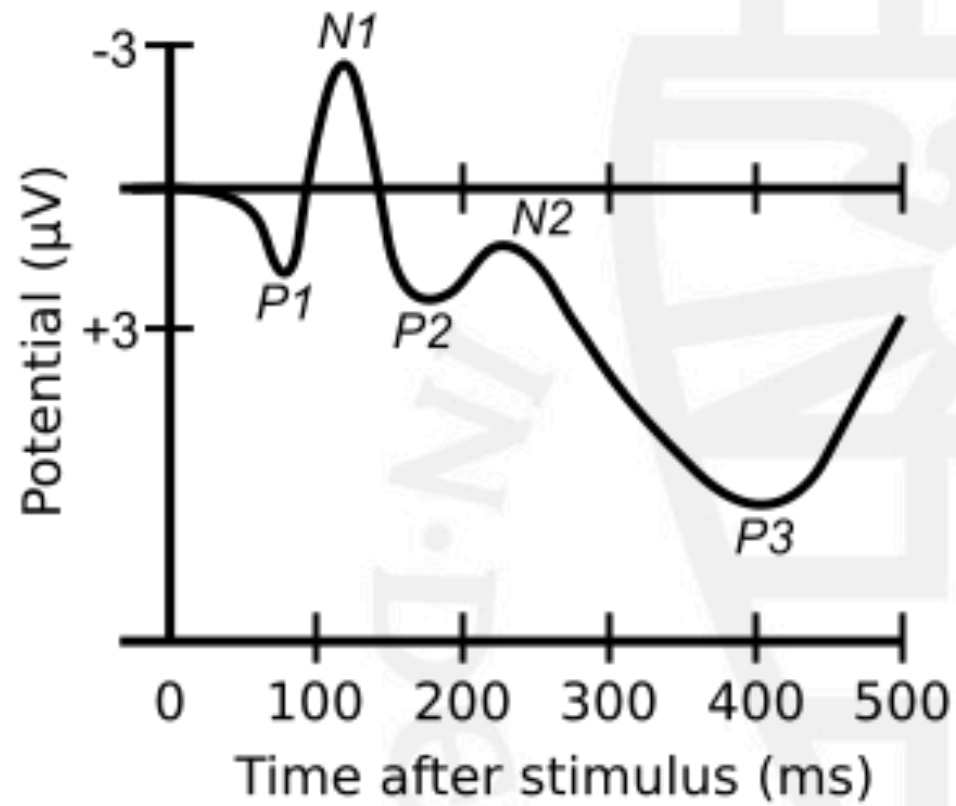
Learning goals

- Understand what ERPs are, their basic characteristics, how they can be influenced, and a number most used ERPs.
- Understand how ERPs can be used in BCI applications
- Know what the P300 ERP is, how to elicit it and why it is useful in BCI.
- Understand how the Farwell-Donchin speller works.
- Know the speller terminology.
- Understand the current debate about overt and covert attention in spellers and influence of artefacts on BCI spellers.

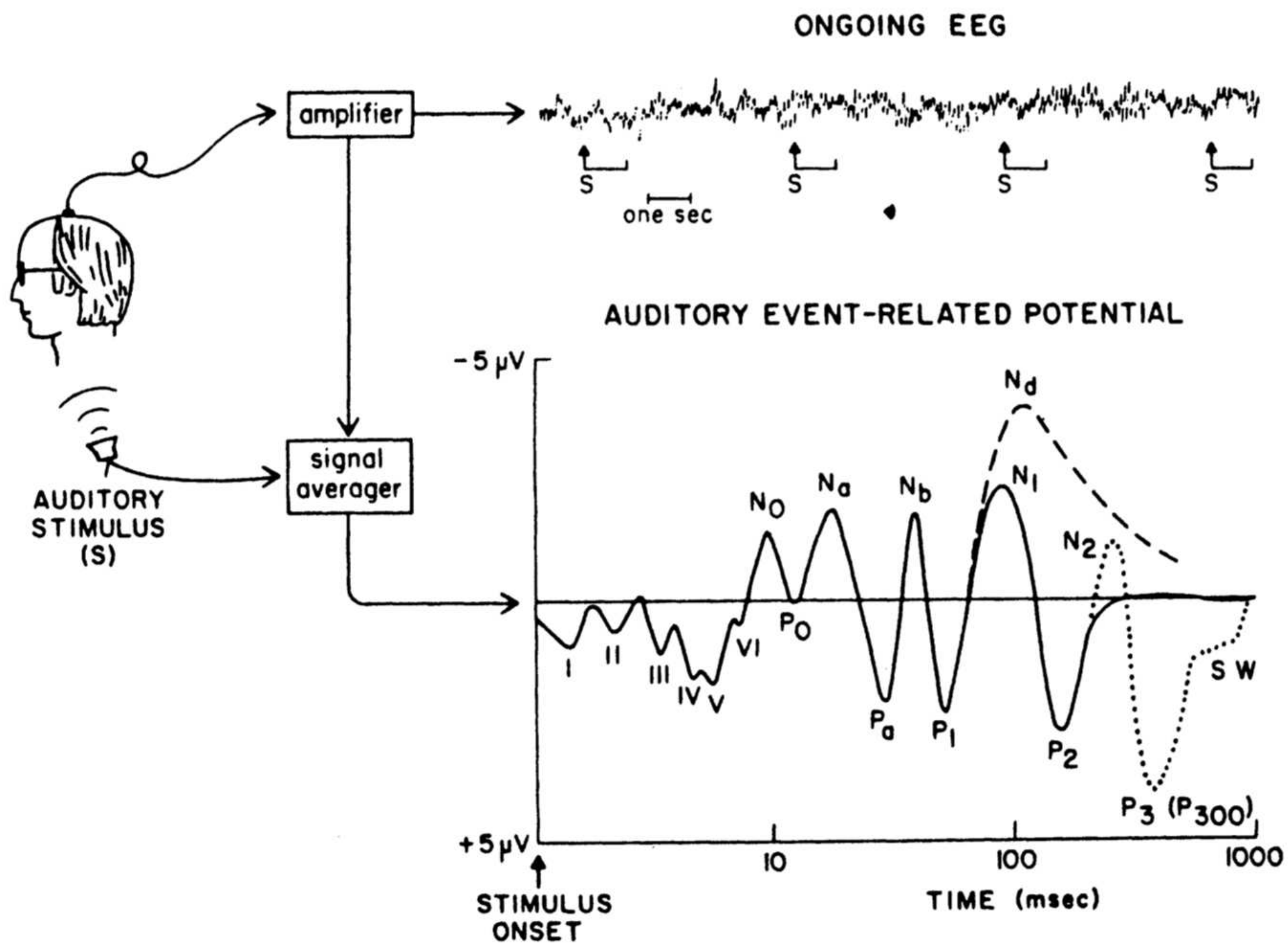
What are ERPs?

Event-related potentials

- Response of the brain to a stimulus event.
- Average of many examples.
- Measured at fixed location on the scalp.
- N for negative, P for positive (beware: negative is sometimes plotted up and sometimes plotted down).
- Numbered sequentially (P1, P2, P3, ...) or by typical latency in milliseconds (N140, P300, ...).



schematic figure from http://en.wikipedia.org/wiki/Event_related_potential



Event-related potentials

Figure from Hilyard & Kutas (1983)
Annual Review of Psychology

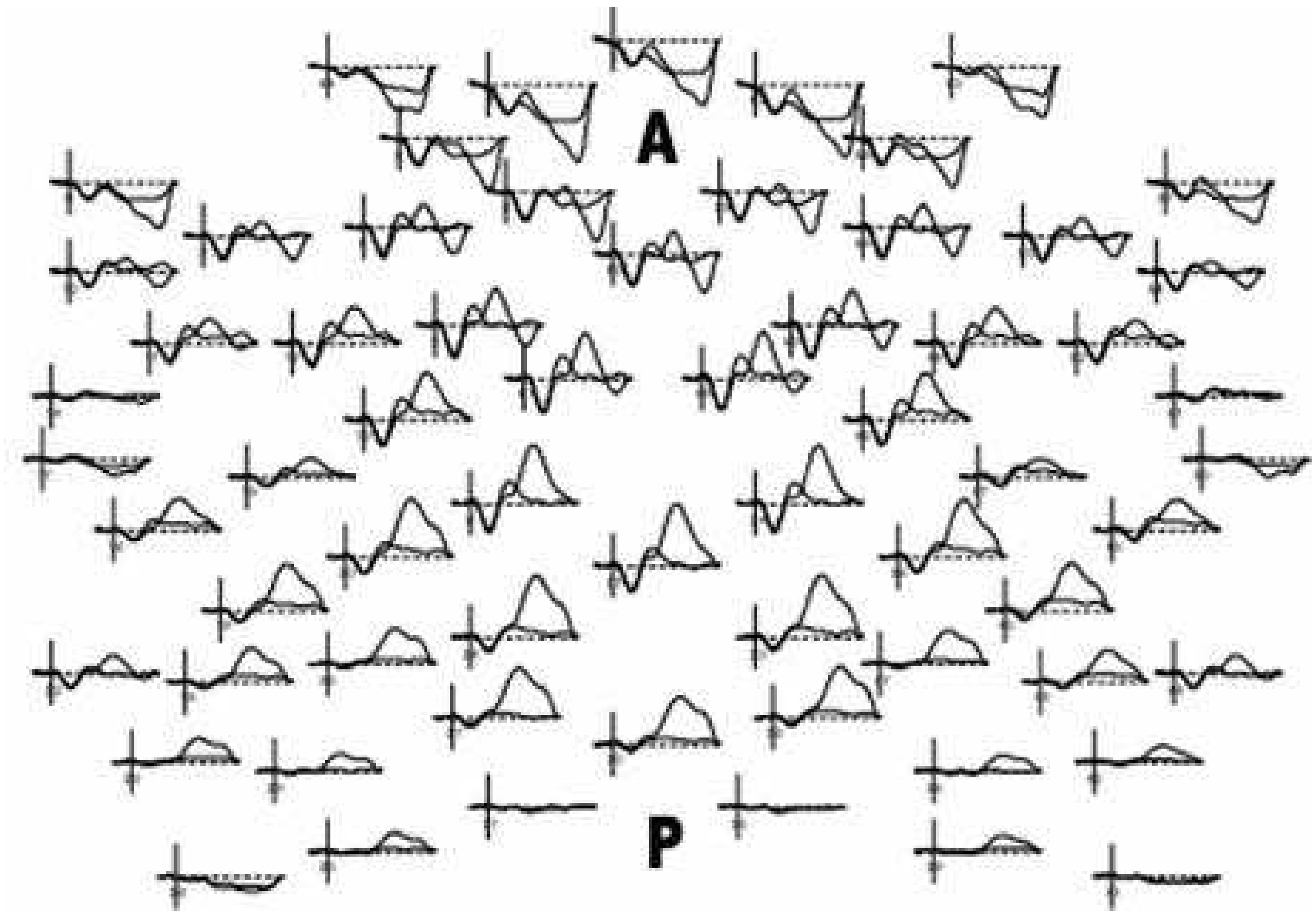


figure from Patel & Azzam (2005) Int. J. Medical Sciences.

The EEG signal is a function of time and *space*. The positivity or negativity of a particular ERP peak depends on which electrode you measure.

Examples of ERPs

ERN: Error Related Negativity (also ErrP), error detection (80-150 ms).

MMN: Mismatch Negativity, detection of deviant stimuli (150-250 ms).

N200: occipital, motion detection (200-350 ms).

P300: central, target detection, ‘aha’ response (300-600 ms).

ELAN: Early Left Anterior Negativity, syntactic processing (100-300 ms).
‘The boys heard Joe’s about story Africa’

N400: centro-parietal, semantic processing (250-500 ms).
‘The boys heard Joe’s orange about Africa’

P600: centro-parietal, syntactic updating (500-800 ms).
‘Time flies like an arrow, fruit flies like a banana’

P300 - Single Stimulus

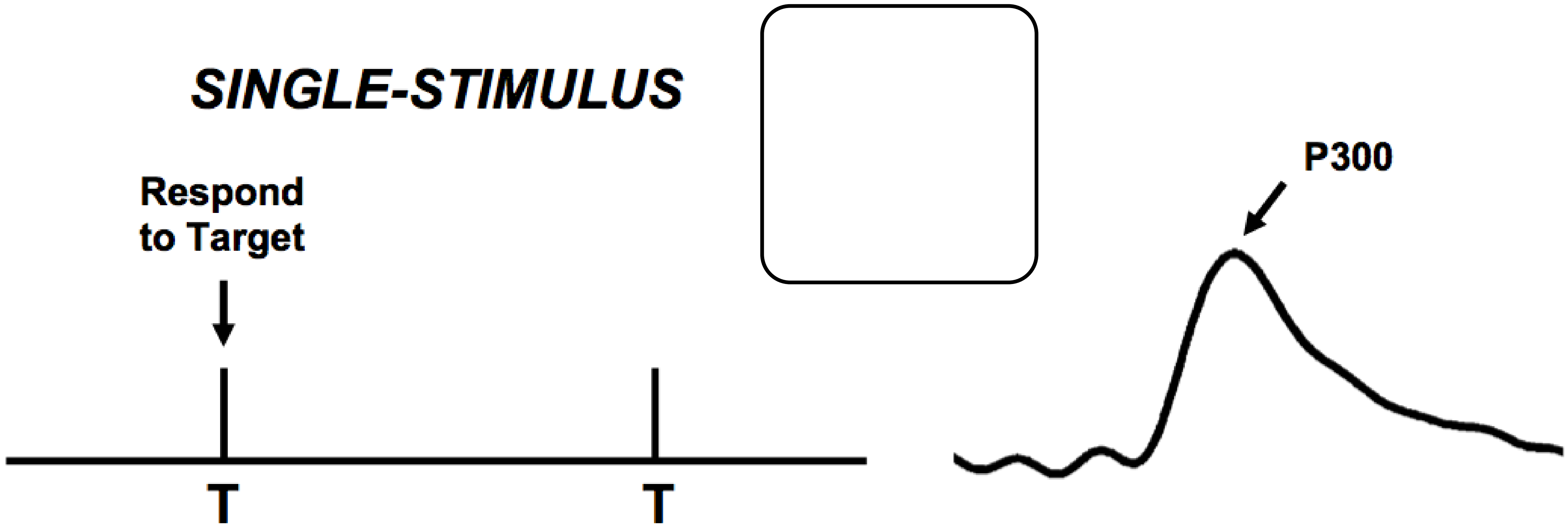


figure from Polich (2007), Clinical Neurophysiology

P300 - Oddball

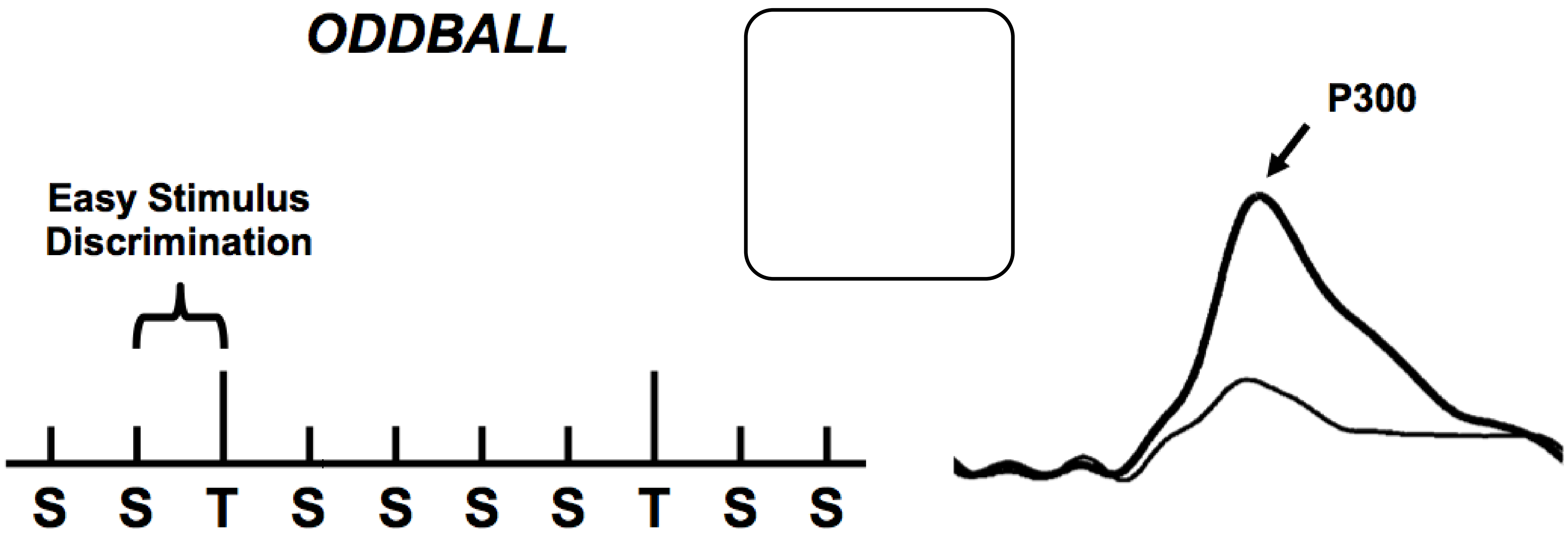


figure from Polich (2007), Clinical Neurophysiology

P300a & P300b - Three Stimuli

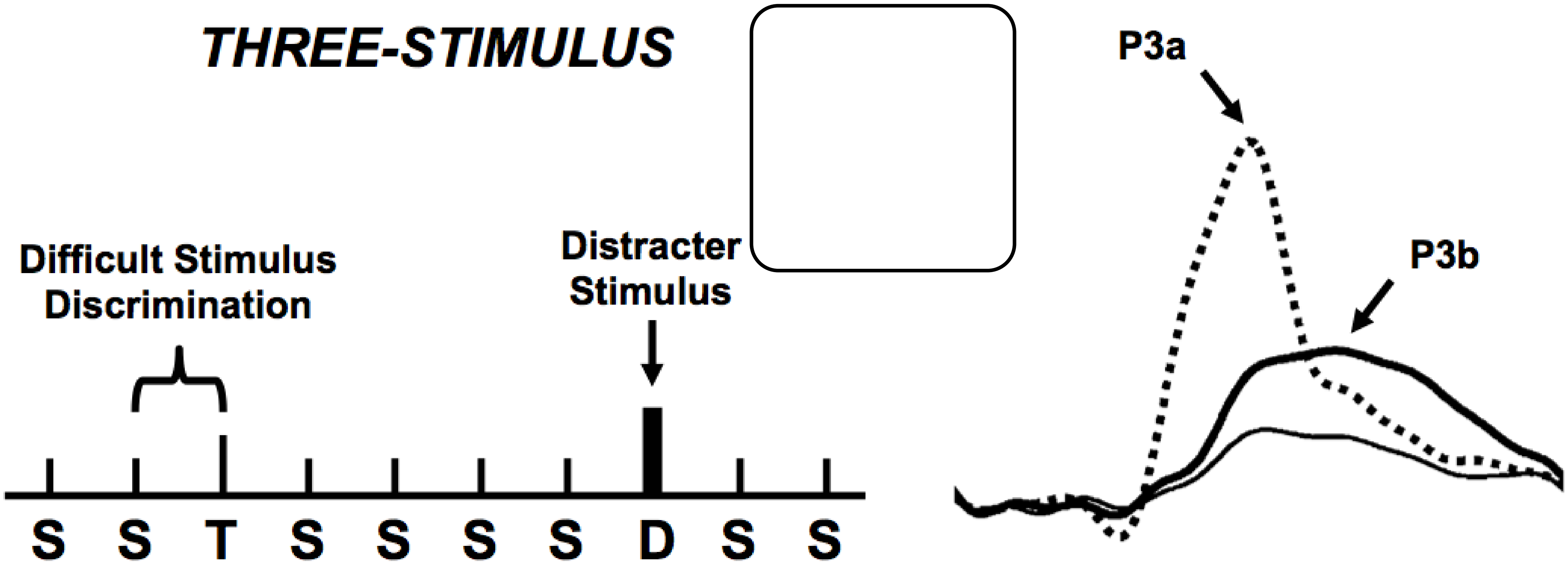


figure from Polich (2007), Clinical Neurophysiology

P300a & P300b - Spatial Distribution

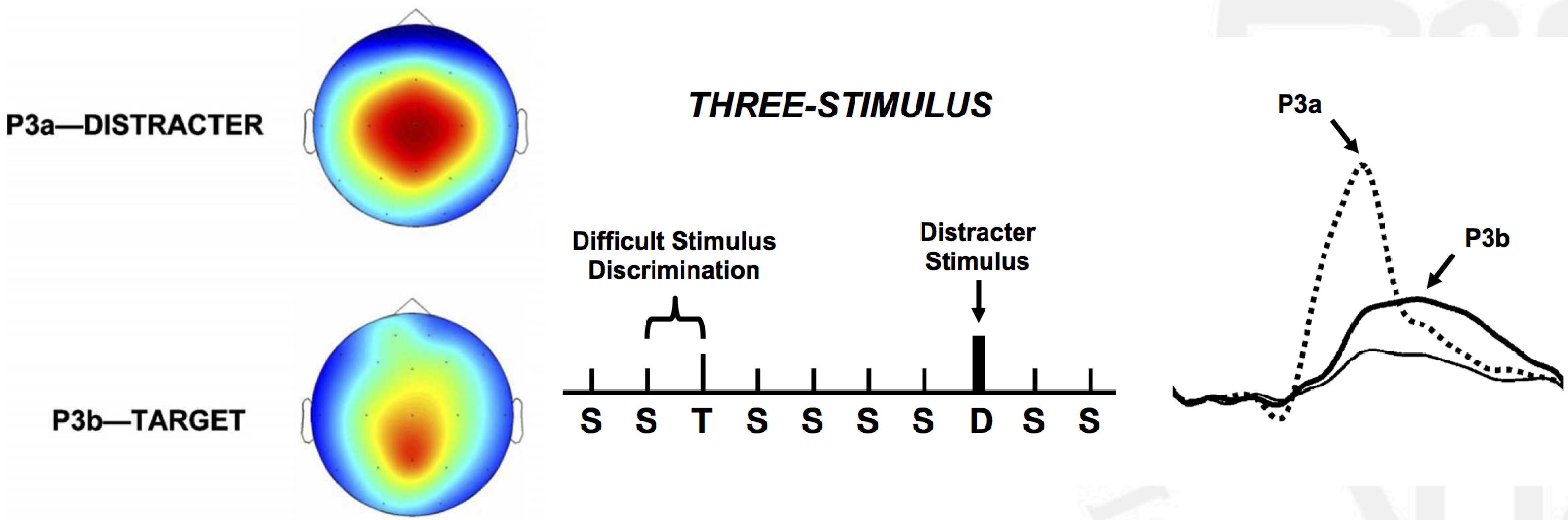
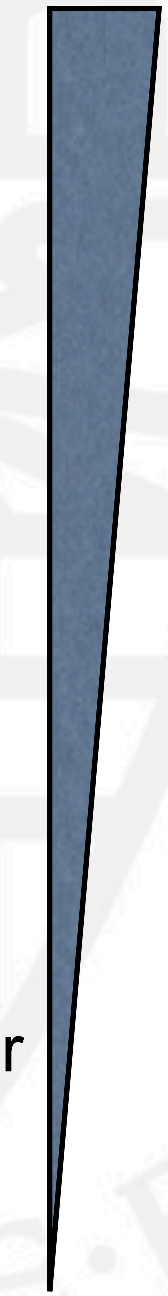


figure from Polich (2007), Clinical Neurophysiology

How can we use ERPs?

Using ERps

Average large number of ERPs



- "Brain Fingerprinting": using P300 and later components, for forensic "guilty knowledge" testing--ruled admissible by US Supreme Court.
- Monitoring the depth of anesthesia.
- Visual perimetry, audiometry, etc. with infants, animals.
- Communication (e.g. the Farwell-Donchin speller).
- "Triage" of potential targets in human stimulus-processing tasks.
- Detection of mistakes (via "error-related negativity" or ERN) in BCI and other tasks.

Classify single ERPs

figures from Para et al. 2008
IEEE Signal Processing Magazine

“Cortically Coupled computer vision”

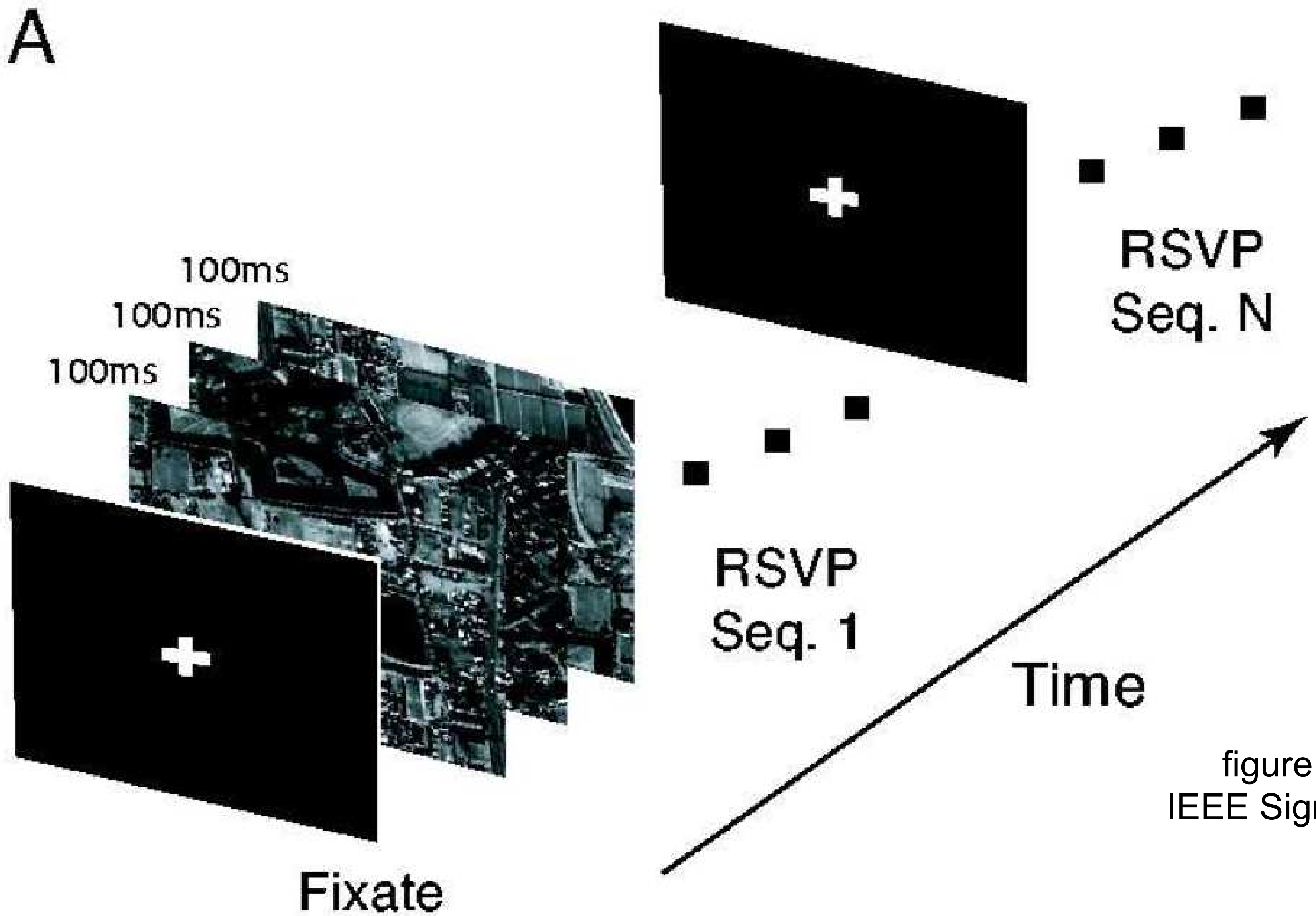


figure from Para et al. 2008
IEEE Signal Processing Magazine

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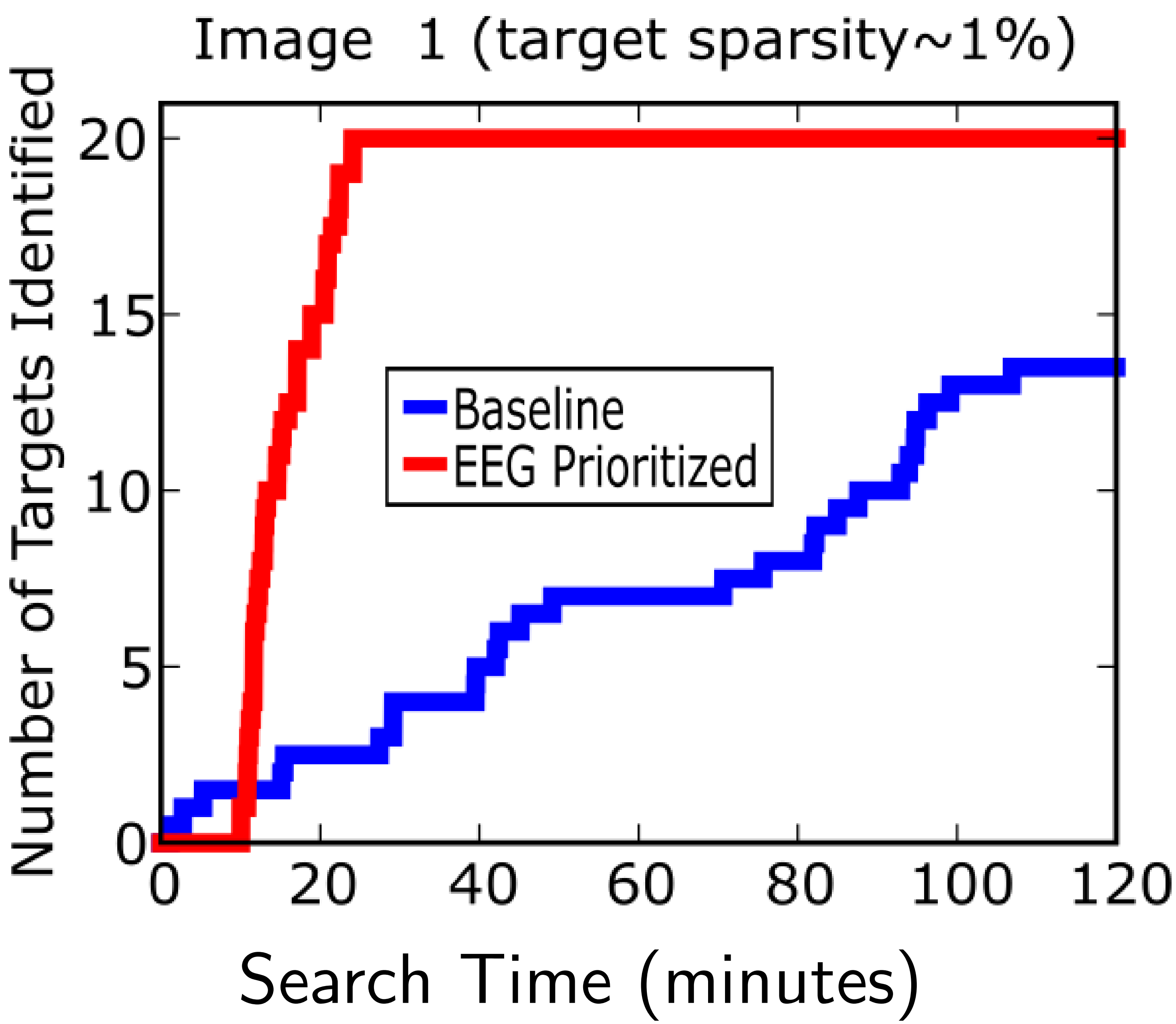


"Cortically Coupled computer vision"

figure from Para et al. 2008
IEEE Signal Processing Magazine

How does the Visual Speller work?

Facts

- First developed by Farwell & Donchin ’88
  - Farwell L & Donchin E (1988): Talking off the Top of your Head: toward a Mental Prosthesis Utilizing Event-Related Brain Potentials. *Electroencephalography and Clinical Neurophysiology* 70: 510–523
- Based on Event Related Potentials
- Mostly P300 ERP
- Not only P300, also P100 and N200.

Terminology

- **Epoch**: short period (500 to 1500 ms) following each stimulus, during which we look for ERPs.
- **Stimulus Onset Asynchrony (SOA)**: the time from the start of one stimulus event (flash) to the start of the next. **NOT**: Inter Stimulus Interval (ISI)
- **Sequence**: one complete cycle of the rows and columns of the grid. If we could classify perfectly, this would be enough information to transmit an arbitrary letter.
- **Trial**: One attempt to transmit a letter or symbol. Single ERPs, and hence single sequences, can rarely be classified perfectly, so a trial often consists of multiple sequences (error-correction by repetition)

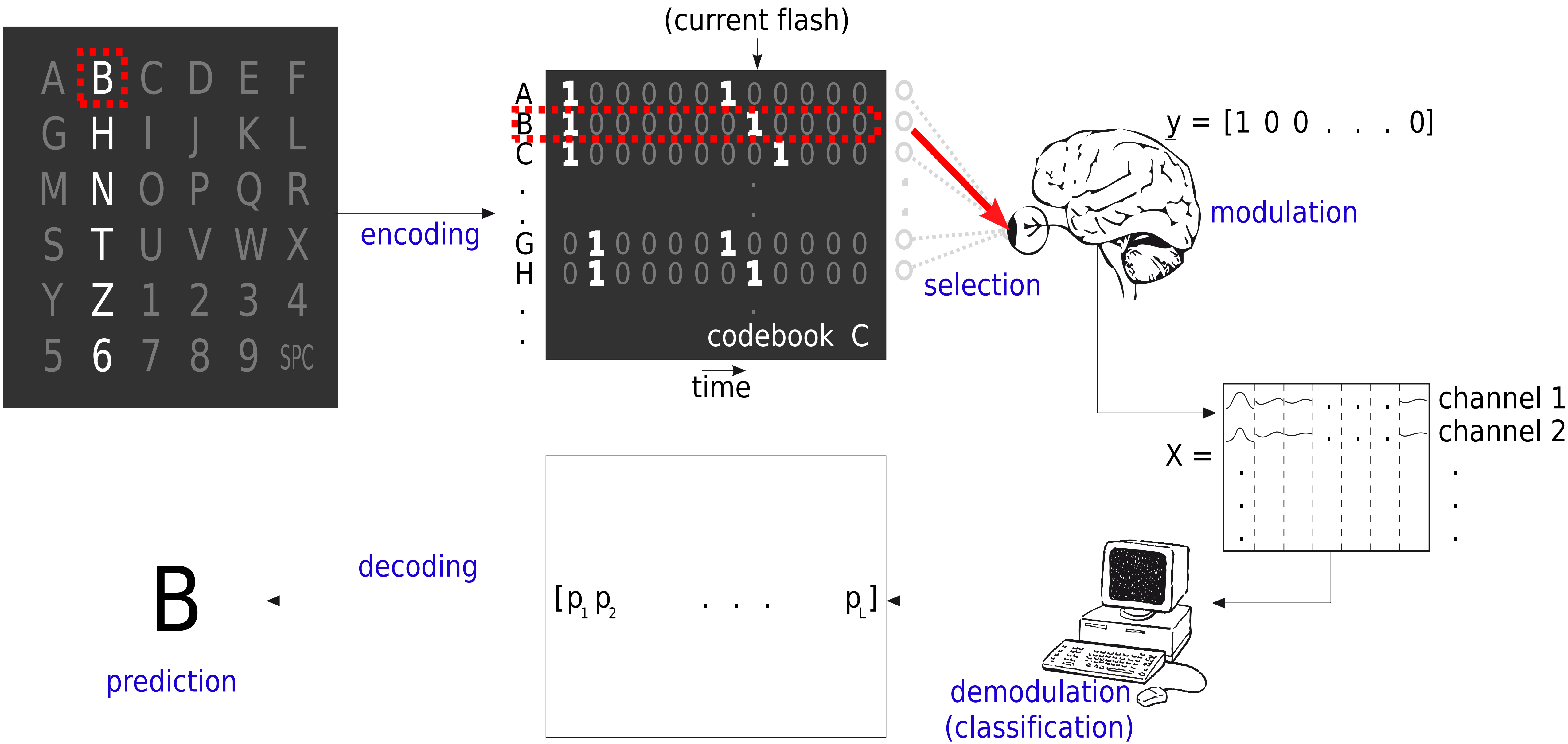
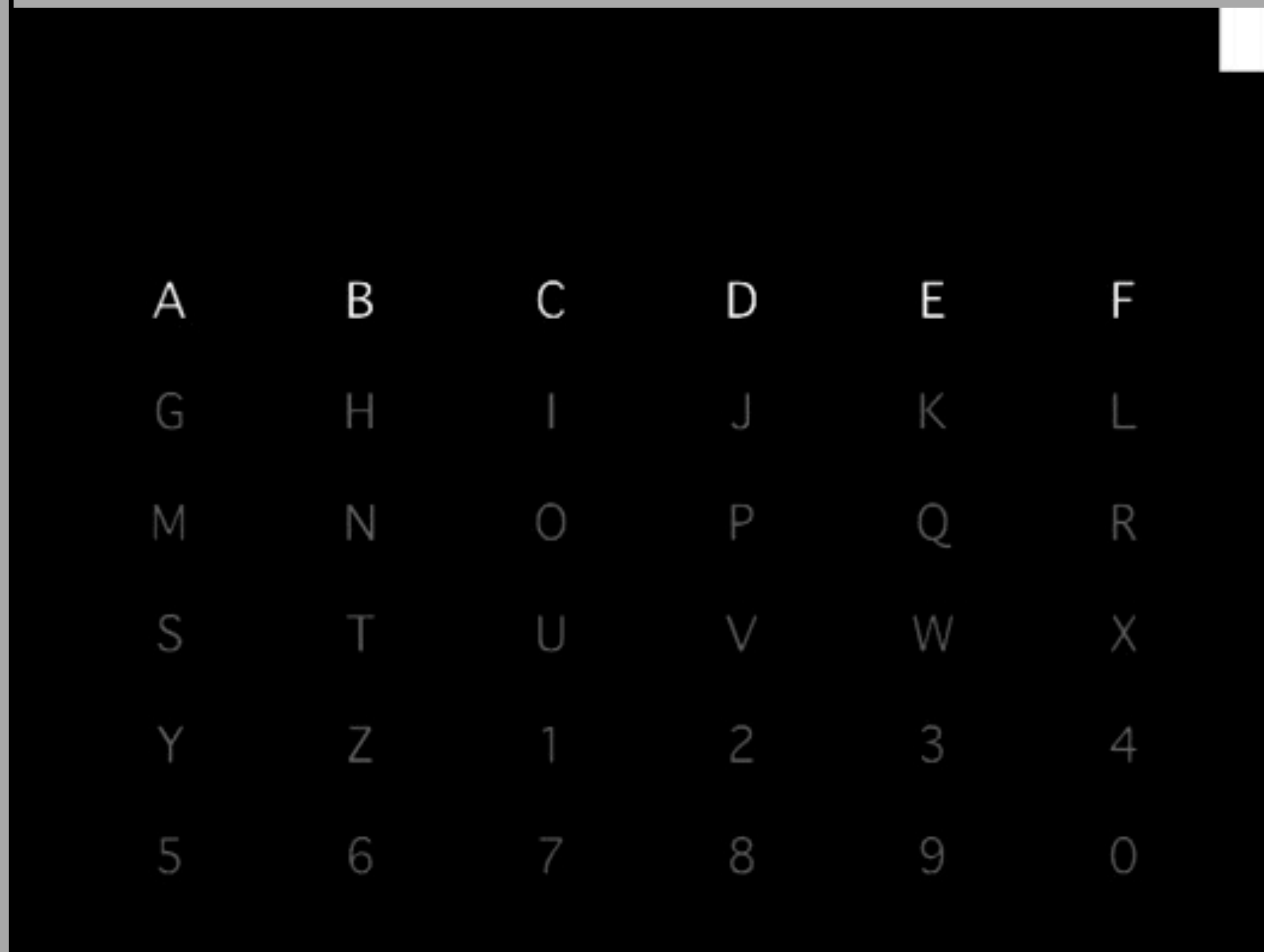
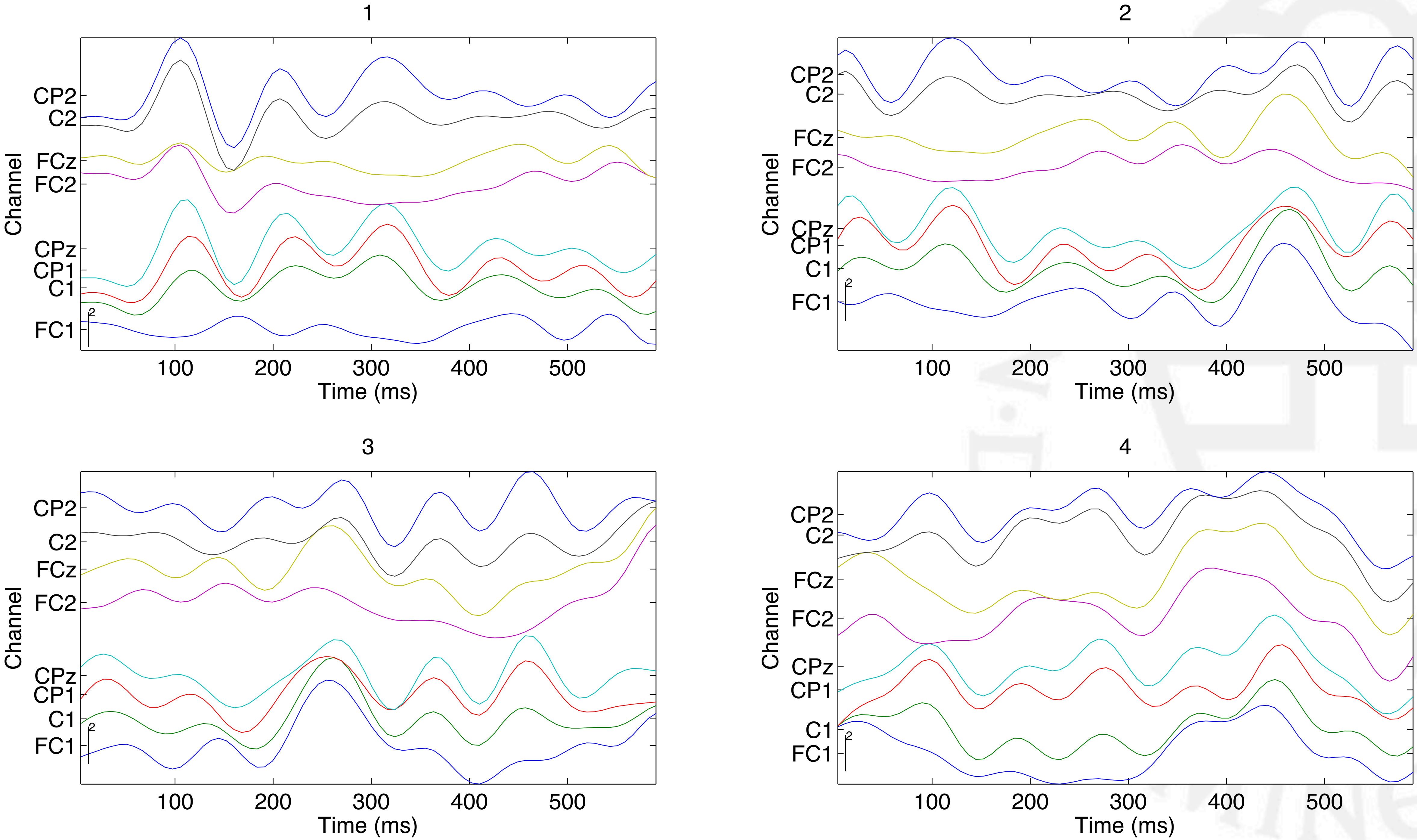


figure from Hill et al. (2009) Advances in Neural Information Processing Systems

A	1	0	0	0	0	0	1	0	0	0	0	0	1	0	0	0
B	1	0	0	0	0	0	0	1	0	0	0	0	1	0	0	0
C	1	0	0	0	0	0	0	0	1	0	0	0	1	0	0	0
D	1	0	0	0	0	0	0	0	0	1	0	0	1	0	0	0
E	1	0	0	0	0	0	0	0	0	0	1	0	1	0	0	0
F	1	0	0	0	0	0	0	0	0	0	0	1	1	0	0	0
G	0	1	0	0	0	0	1	0	0	0	0	0	0	1	0	0
H	0	1	0	0	0	0	0	1	0	0	0	0	0	1	0	0
I	0	1	0	0	0	0	0	0	1	0	0	0	0	1	0	0
J	0	1	0	0	0	0	0	0	0	1	0	0	0	1	0	0
K	0	1	0	0	0	0	0	0	0	0	1	0	0	1	0	0
L	0	1	0	0	0	0	0	0	0	0	0	1	0	1	0	0
M	0	0	1	0	0	0	1	0	0	0	0	0	0	0	1	0
N	0	0	1	0	0	0	0	1	0	0	0	0	0	0	1	0
O	0	0	1	0	0	0	0	0	1	0	0	0	0	0	1	0
P	0	0	1	0	0	0	0	0	0	1	0	0	0	0	1	0
Q	0	0	1	0	0	0	0	0	0	0	1	0	0	0	1	0
R	0	0	1	0	0	0	0	0	0	0	0	1	0	0	1	0
S	0	0	0	1	0	0	1	0	0	0	0	0	0	0	0	1
...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...



Single trial

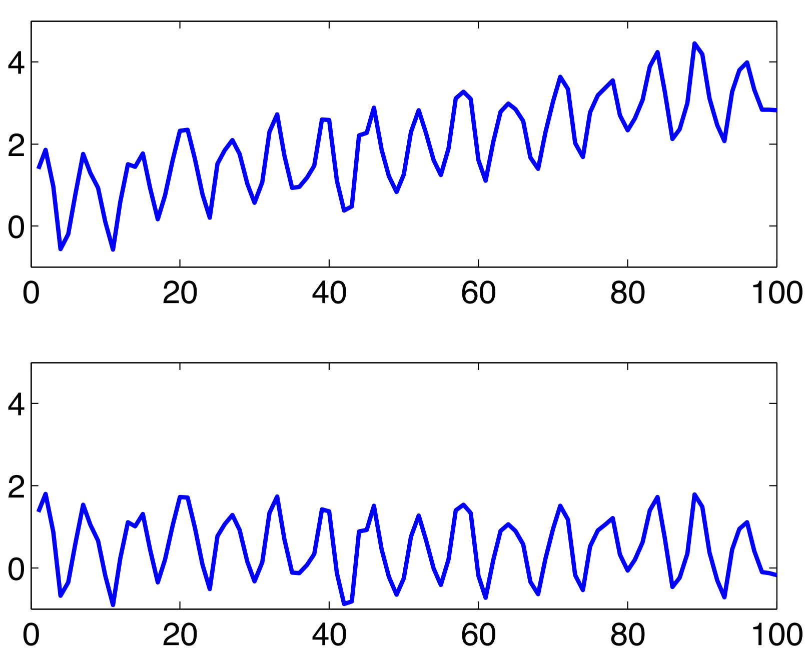


Preprocessing

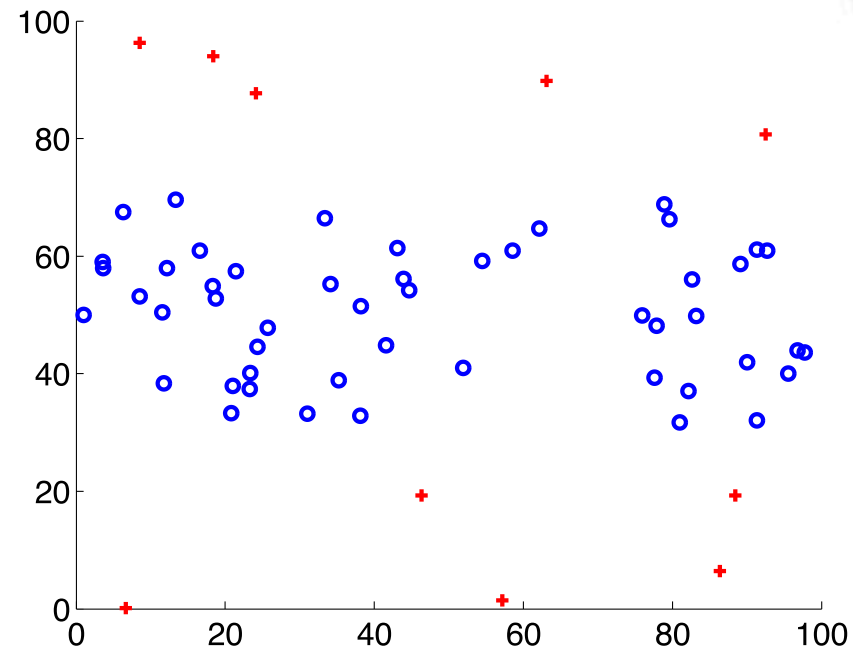
Clean up noisy data by:

- Detrending
- Removing outliers
- Common Average Reference (CAR)
- Removing eye artifacts
- (Spectrally) Filtering the data

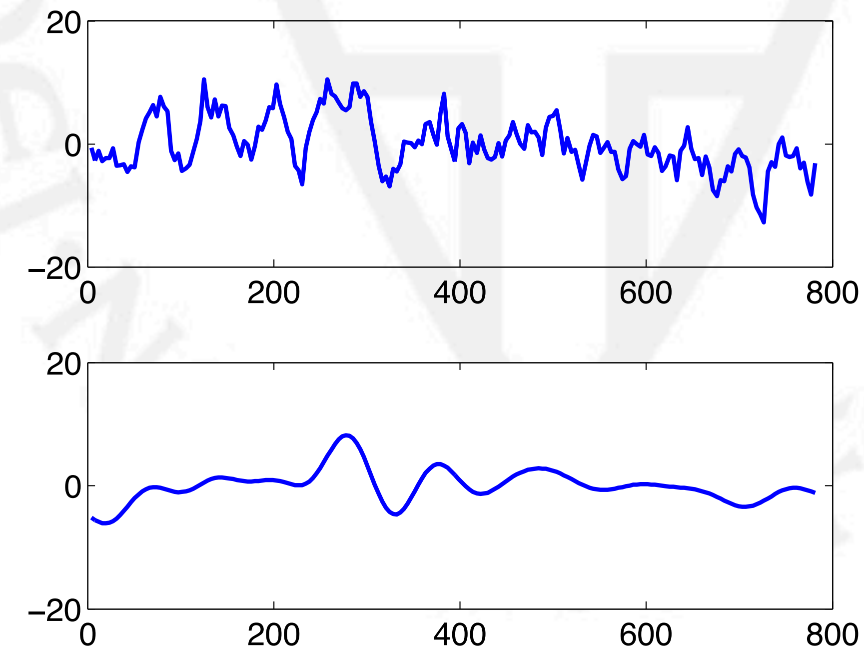
Detrend



Outlier



Filter



Machine Learning: Classification

Algorithms that are able to assign a label to the data.

Number of classes.
Here, two or binary.

Supervised vs. unsupervised learning algorithms.

We use supervised, so we need labels.

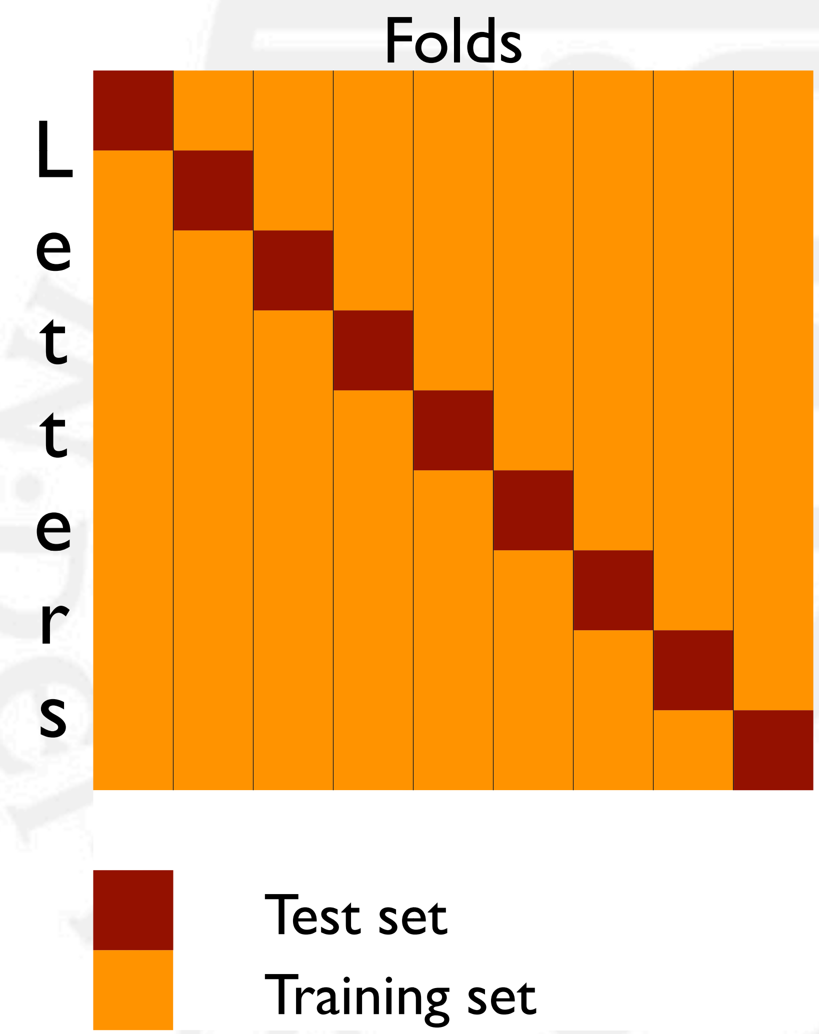
Offline versus online.

Training a Classifier

Input:
1. Cleaned data (features x examples)
2. Labels (# examples)

Overfitting / generalization
Folding
Hyperparameters

Output:
1. Classification rate (%)
2. Weight vector (# features)



Using the Trained (Linear) Classifier

Simple! Multiply the classifier weights with the new data:

$$\begin{pmatrix} f_1 \\ f_2 \\ \vdots \\ f_n \end{pmatrix} \cdot \begin{pmatrix} w_1 & w_2 & \dots & w_n \end{pmatrix} = dv$$

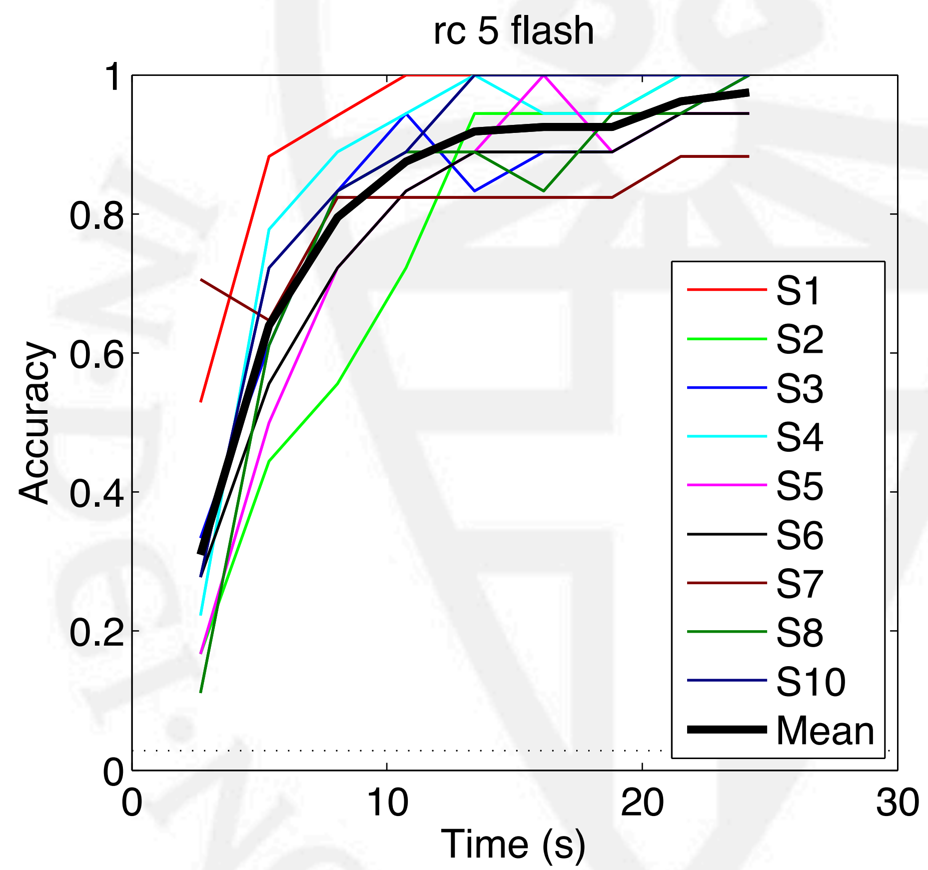
The class is determined by sign(dv):

+	Class 1
-	Class 2

Decoding

Codebook * decision value, max over letters.

$$argmax\left(\begin{pmatrix} 1 & 0 & 0 & 0 & \dots & 0 \\ 1 & 0 & 0 & 0 & \dots & 0 \\ 1 & 0 & 0 & 0 & \dots & 0 \\ 1 & 0 & 0 & 0 & \dots & 0 \\ \vdots & \vdots & \vdots & \vdots & \vdots & \vdots \\ 0 & 0 & 1 & 0 & \dots & 1 \end{pmatrix} \cdot \begin{pmatrix} dv_1 \\ dv_2 \\ dv_3 \\ \vdots \\ dv_n \end{pmatrix}\right)$$



Overt vs Covert attention

- Most P300-speller tests are performed with healthy subjects who look directly at (foveate) the target of interest.

- For users who can do this:
  - Are we relying (partially? mostly?) on gaze-dependent features of the EEG (e.g. visual evoked potentials from areas representing the fovea)?
  - Would an eye-tracking system do just as well, or better?

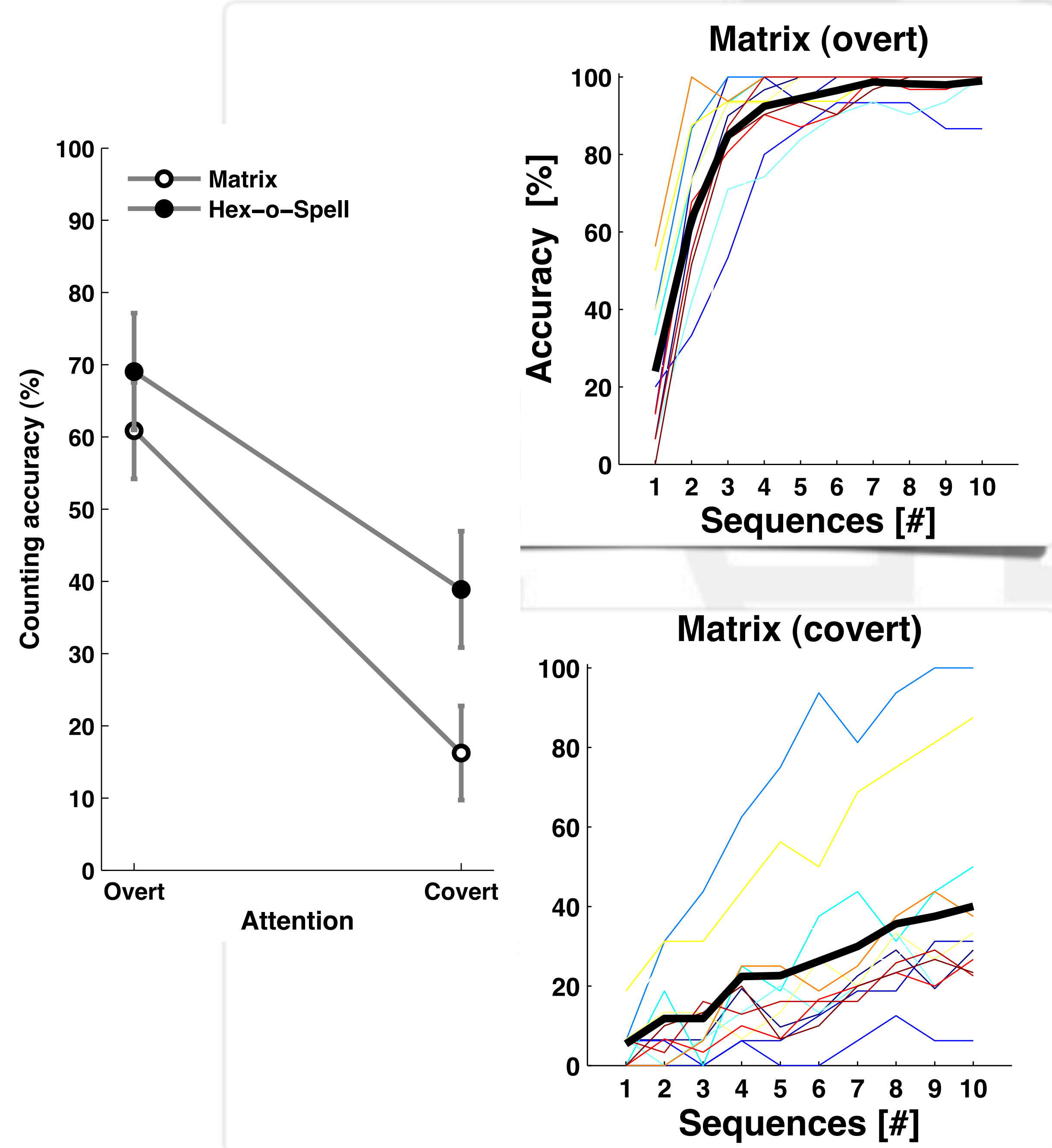
- For users who cannot:
  - Would the task become too difficult?
  - Would the system suffer interference from the evoked potentials caused by whatever the user is fixating?

- For anyone:
  - Artefacts time-locked to the stimulus of interest will also lead to “successful” BCI performance.

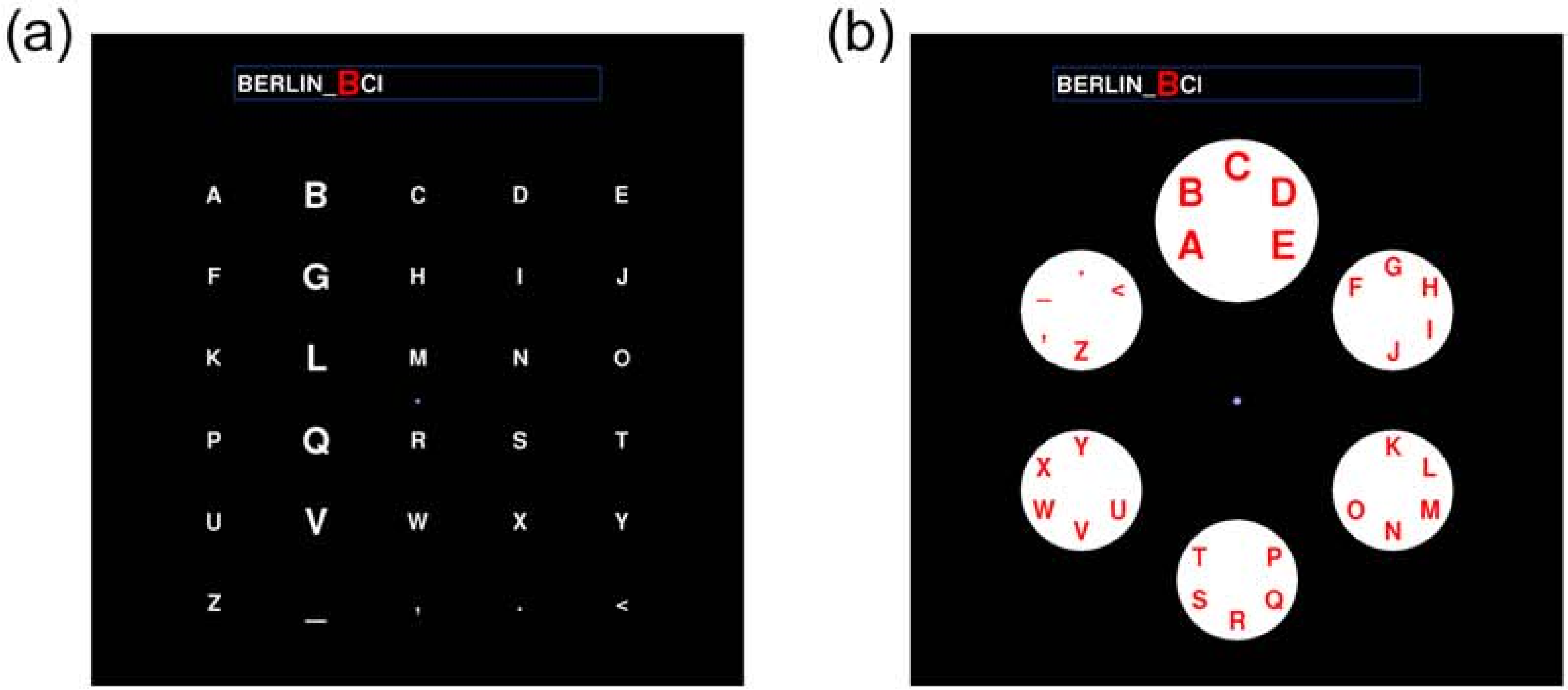
Overt vs covert attention

- Treder and Blankertz (2010, Behavioral and Brain Functions), performed a systematic comparison between overt and covert attention in spellers.

- They compared classification rate, detection error rates and ERP components.



figures from Treder et al. 2010
Behavioral and Brain Functions

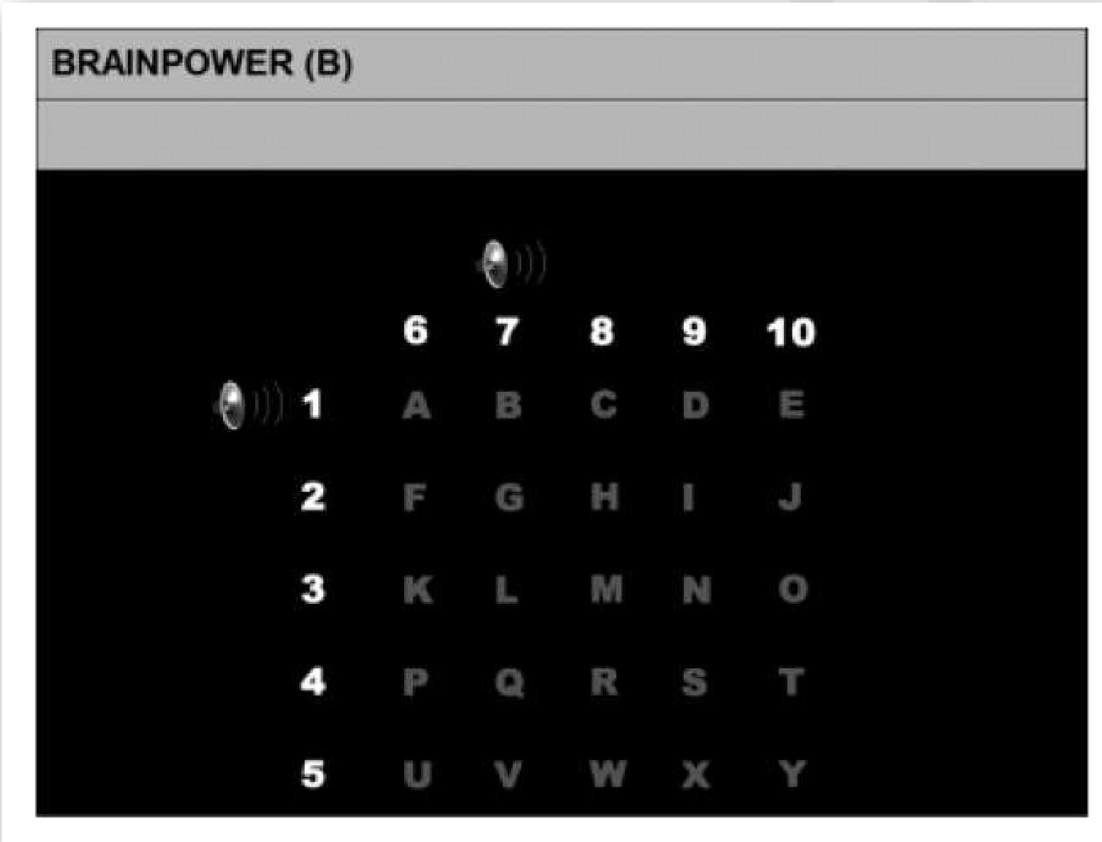


figures from Treder et al. 2010
Behavioral and Brain Functions

Matrix vs hex-o-spell

An Auditory p300 speller

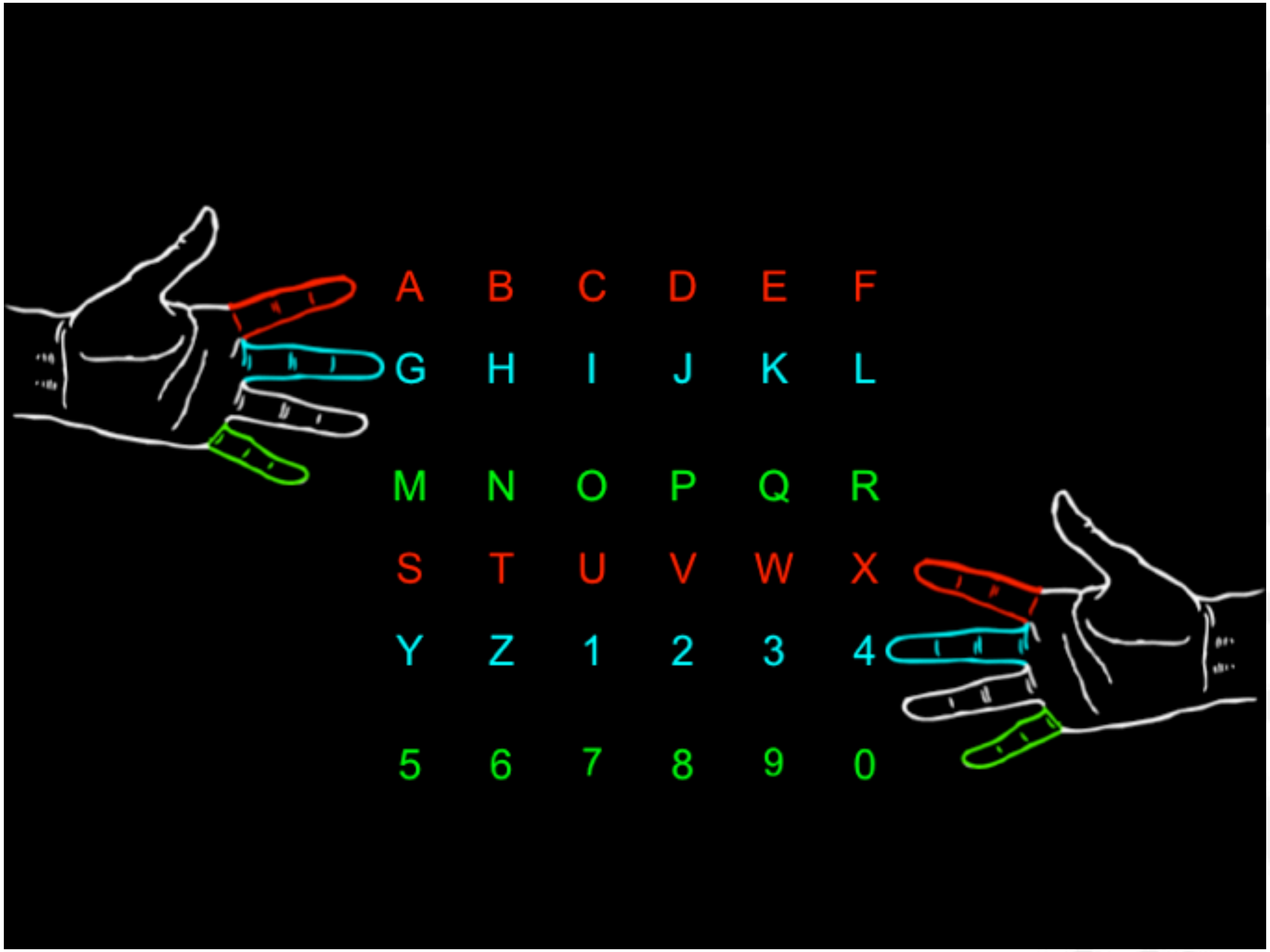
- Furdea et al. 2009, Psychophysiology:
- Auditorily presented numbers encode the rows and columns



Tactile speller

Same principle as auditory speller.

Use braille stimulators to stimulate 6 fingers.



Tactile Speller

Summary

- ERPs are electrical signals which can be measured as peaks and troughs in the EEG.
- Their appearance is correlated in time with some stimulus event.
- Each ERP component had a characteristic latency, shape and scalp distribution.
- Some ERP components' amplitude and latency can be influenced by endogenous factors (e.g. attentional state, arousal level, intentions, expectations) as well as exogenous factors (stimulus characteristics).
- They can be extracted best by time-locked averaging of the voltage signal from a large number of epochs.
- However, classification of small numbers of these epochs is also possible, leading to applications in brain-computer interfacing.
- The most closely studied of these is the Farwell-Donchin speller, exploiting the user's (overt and covert) attention to one out of a set of visual stimuli.