

A visual Brain-Computer Interface for gaze-free communication

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The Locked-in Syndrome



Paralysis with impaired speech:
the **Locked-in Syndrome**

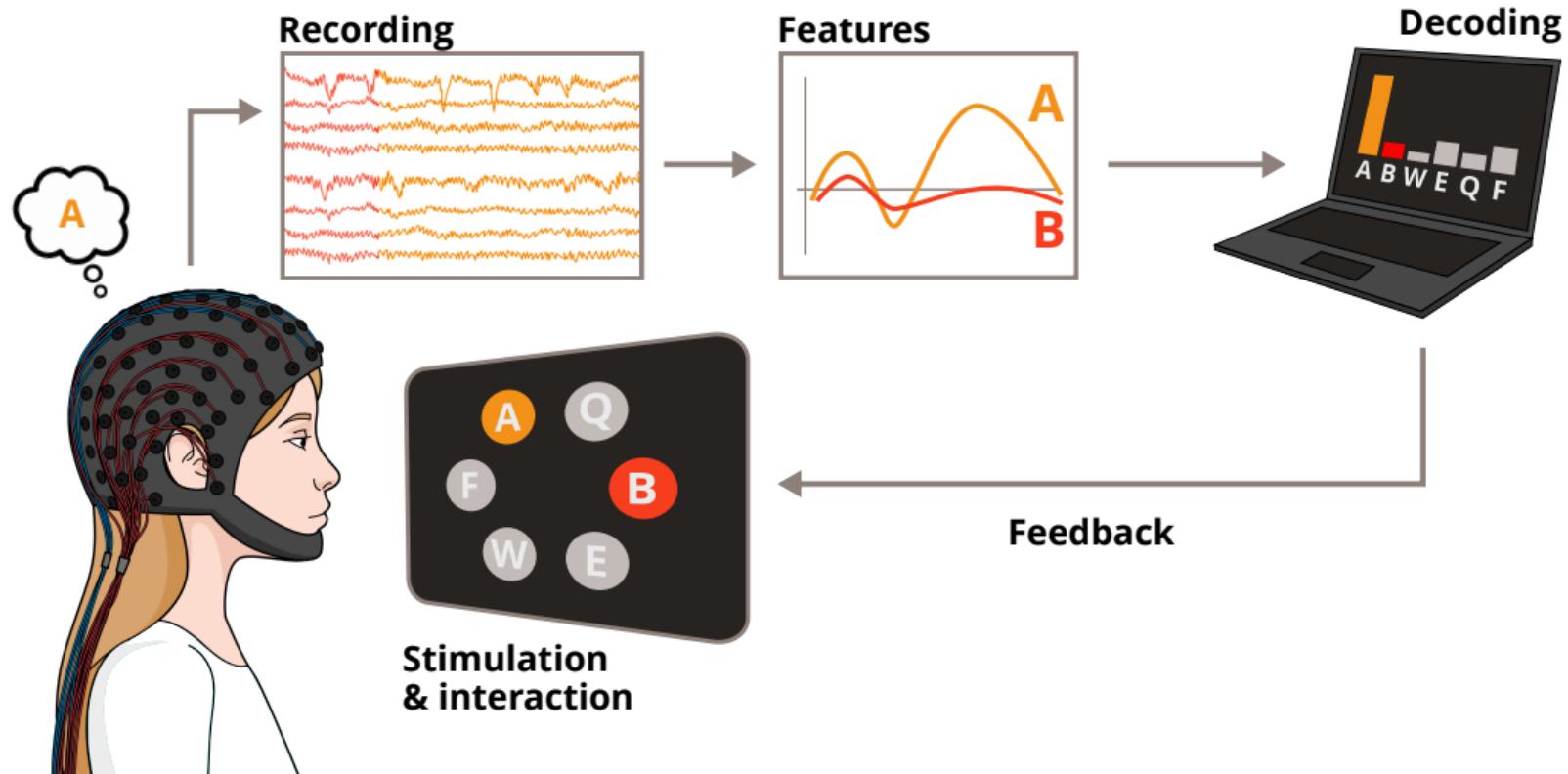
Due to

- ▶ Stroke
- ▶ Traumatic brain injury
- ▶ Neurodegenerative diseases
- ▶ ...

Communication requires
assistive technology

What if muscle control is
insufficient?

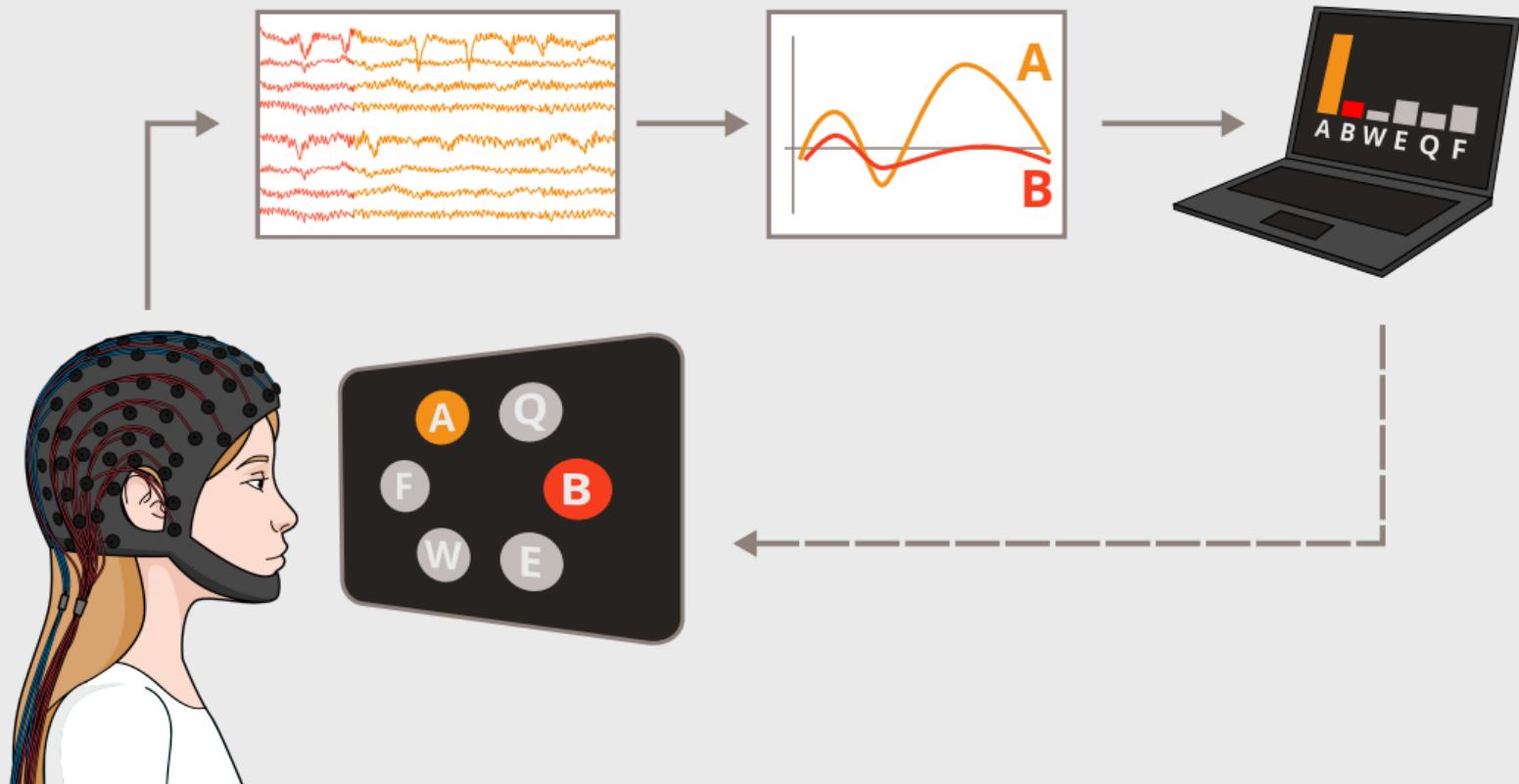
The Brain-Computer Interface



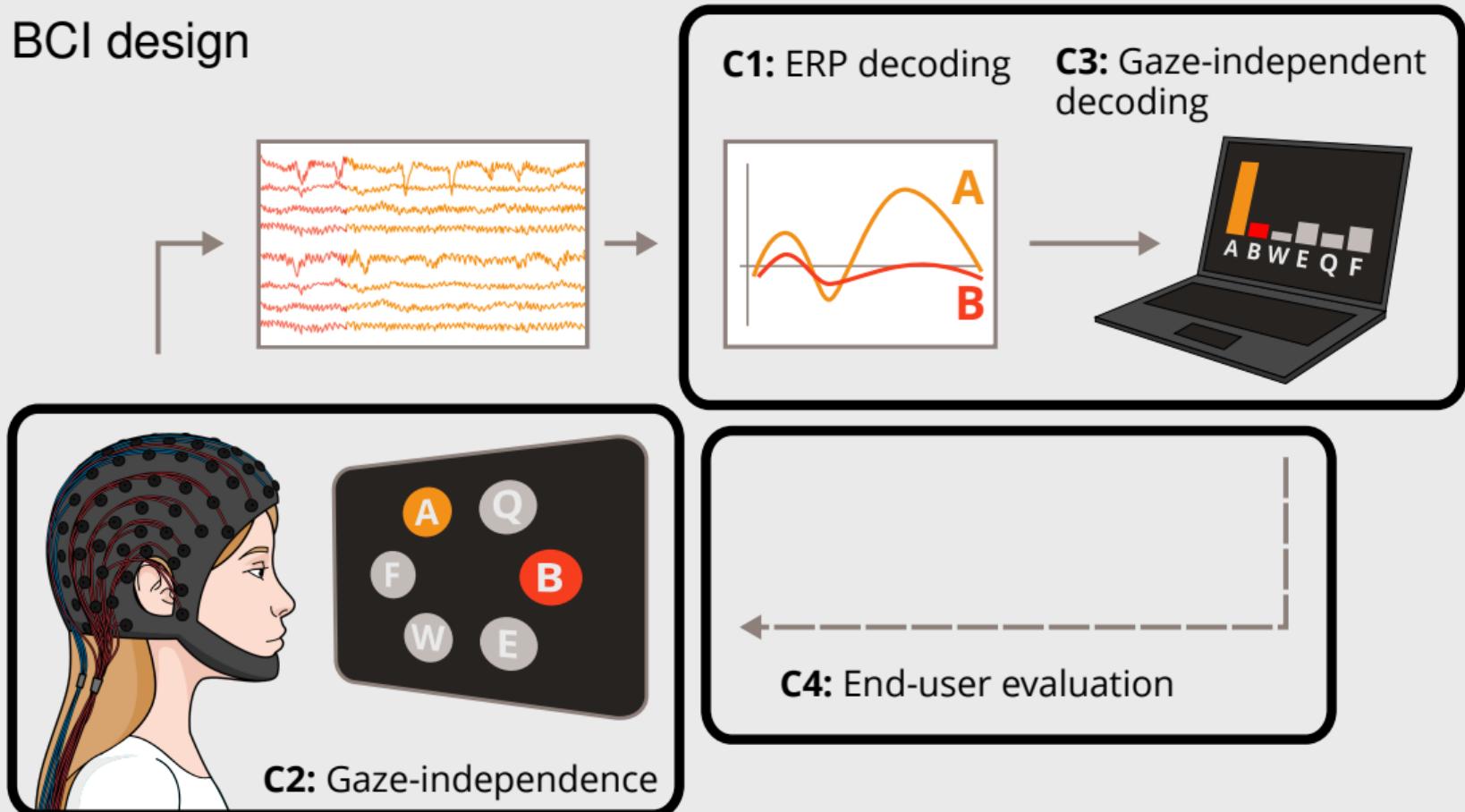
Research question

How can we optimize **BCI** assistive technology design to make it more **efficient** and **inclusive**?

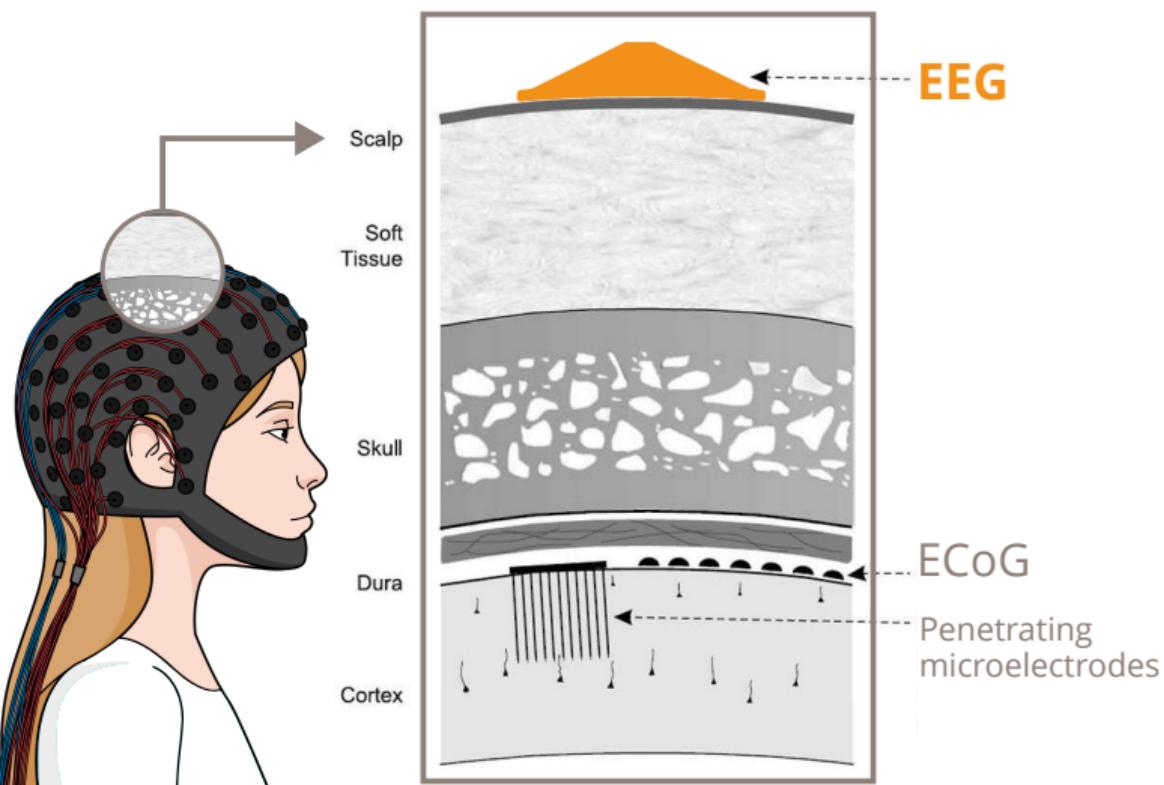
BCI design



BCI design



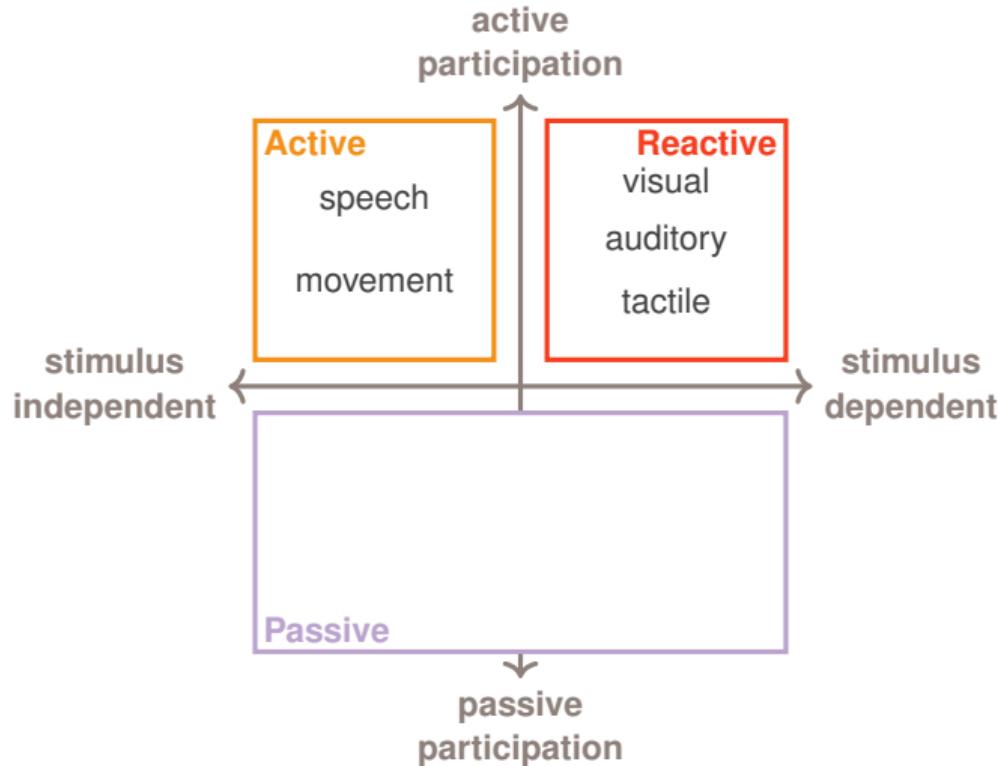
Recording the brain activity



EEG measures the electrical field on the scalp:

- + Non-invasive
- + Cheap
- Limited resolution
- Low signal-to-noise ratio

BCI paradigms for communication



Active BCIs

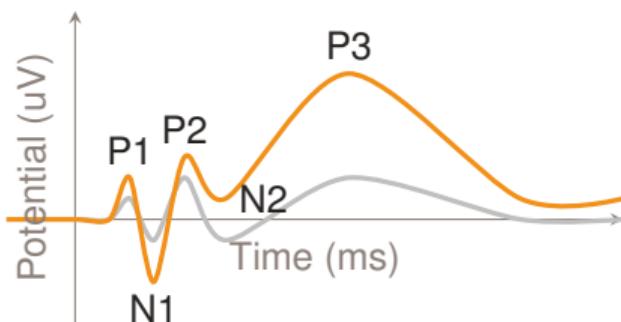
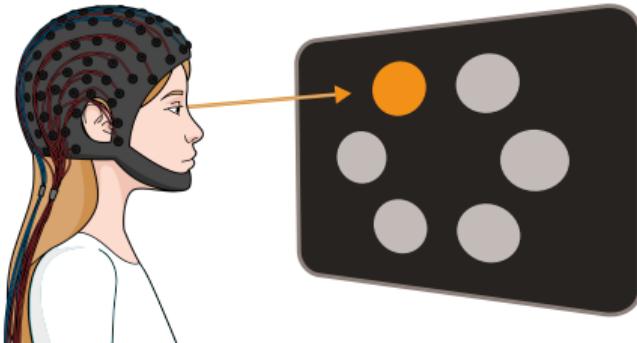
- + Intuitive, self-paced
- High speed requires invasive

Reactive BCIs decode reactions to attended stimuli

- Less intuitive
- + Fast stimulation
- + Suited for EEG

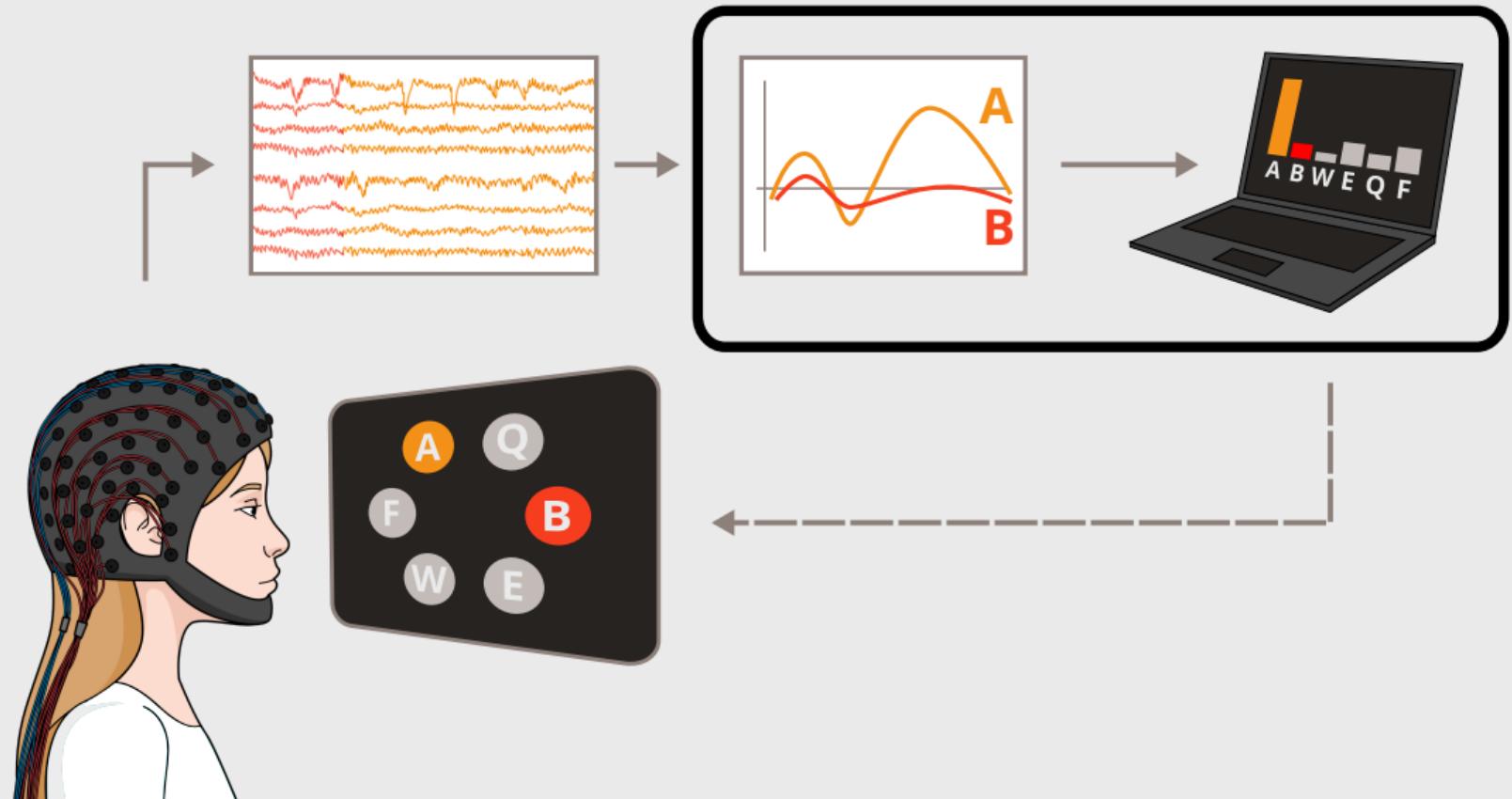
Visual reactive BCIs are a good candidate.

The visual event-related potential paradigm



1. Stimuli flash one by one
2. Flashes evoke ERPs
3. User attends a stimulus
4. ERP components are modulated by attention
5. Decode target based on timing and components

C1. Spatiotemporal ERP decoding



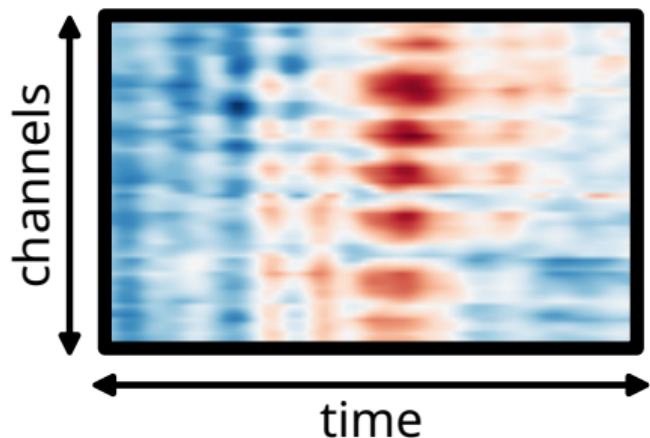
Problem: ERP responses can be difficult to extract

Low single-trial signal-to-noise ratio

- ▶ Machine learning models must be trained to decode ERPs

Each response is a sample with
 $\# \text{ features} = \# \text{ channels} \times \# \text{ time points}$

- ▶ High number of features
(channels \times times)
- ▶ Short calibration time
results in low sample size



features >> # samples

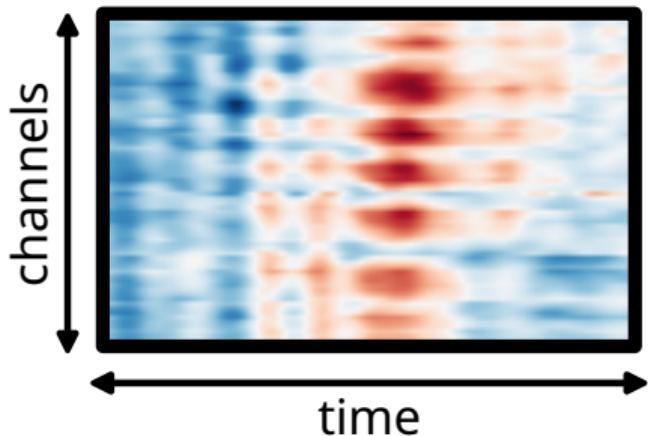
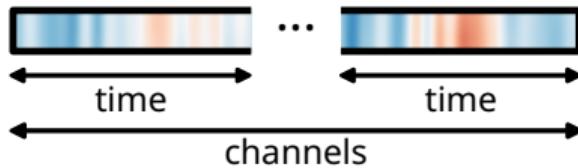
Retaining space-time structure enhances performance

Data are usually flattened before classification

- ▶ ignores channel-time point structure

Assumptions on **data structure**

- ▶ yield strong regularization
- ▶ speed up training



Covariance matrix regularization

Van Den Kerchove, Libert, et al., 2022

Time x space (channels * samples)

Time x space (channels * samples)

Linear decoders require covariance estimation and inversion

Imprecise due to high dimensionality

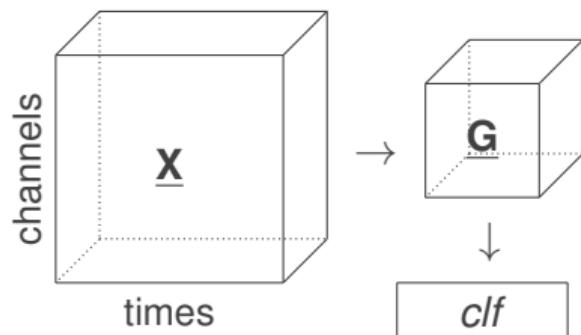
Repetitive structure can be expressed as separate space and time covariance

Saves computation time and improves accuracy for low data availability

Tensor feature extraction

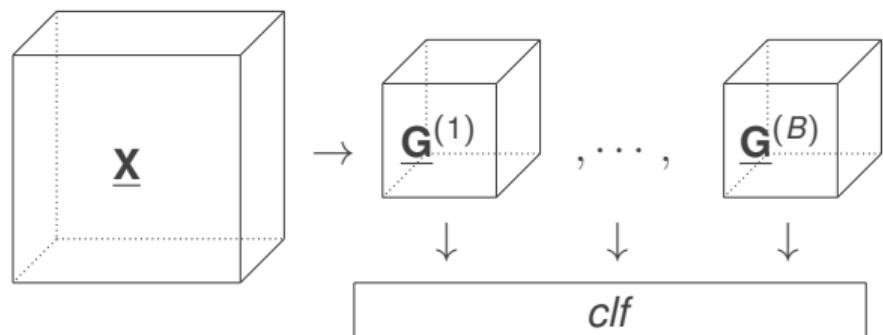
Van Den Kerchove, Si-Mohammed, et al., submitted

Tensor discriminant analysis



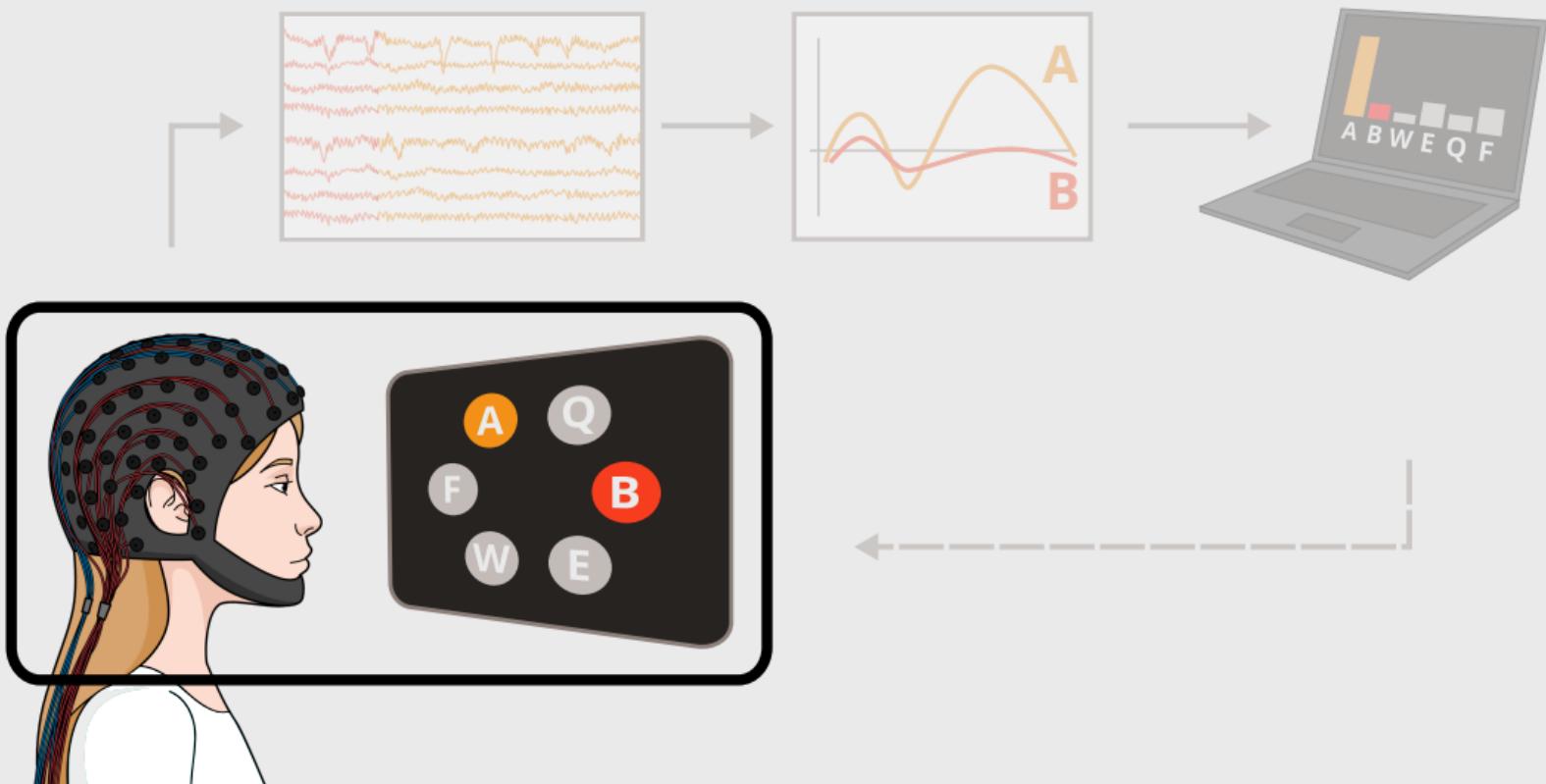
Phan et al., 2010

Block-term tensor discriminant analysis



- + More flexible
- + Retains structure
- More parameters
- Heuristic model selection
- Validated with 4 open datasets

C2. Gaze-independence

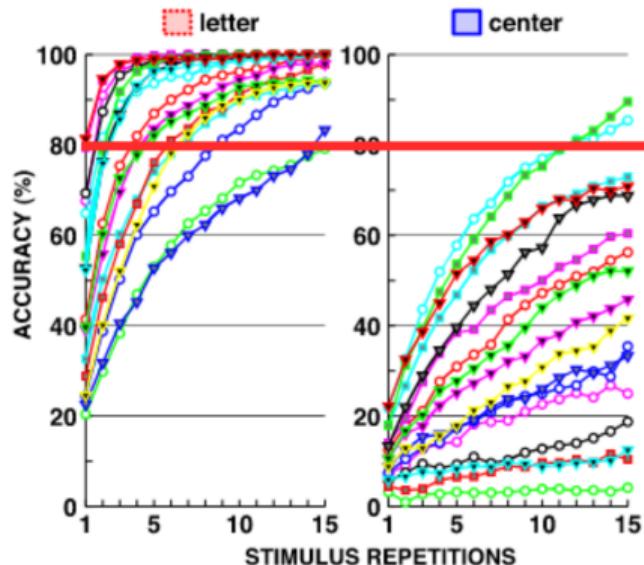


Problem: Eye motor impairment prevents gazing at targets

Visual skills related to disease affect BCI operation Fried-Oken et al., 2020

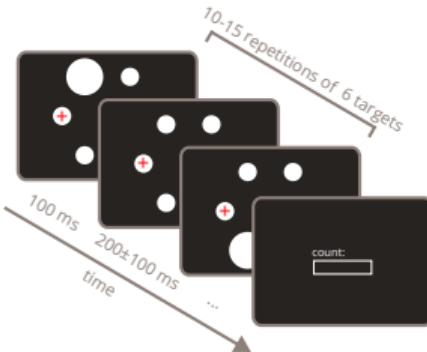
- ▶ Discomfort fixating
- ▶ Restricted movement
- ▶ Involuntary movements

Decoding relies on **visual ERP** components Treder et al., 2010

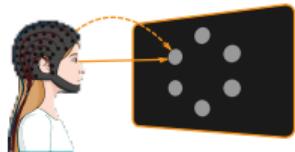


Ron-Angevin et al., 2019

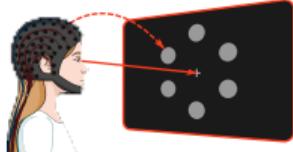
Covert visuospatial attention experiment



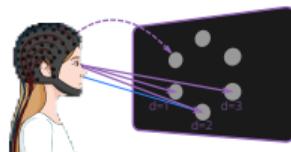
Overt VSA



Covert VSA



Split VSA

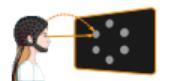


CVSA-ERP dataset

- ▶ 15 subjects, ± 11 h stimulation
- ▶ Hex-o-Spell interface
Treder et al., 2010
- ▶ Discrete gaze-independence conditions

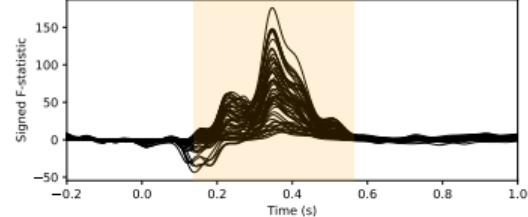
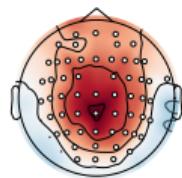
Van Den Kerchove, Si-Mohammed, et al.,
2024

Evoked ERP components

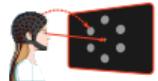
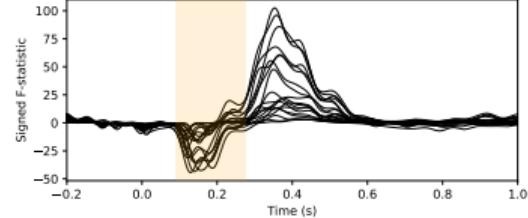
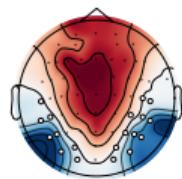


Overt VSA

0.140 - 0.564 s

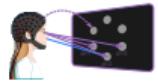
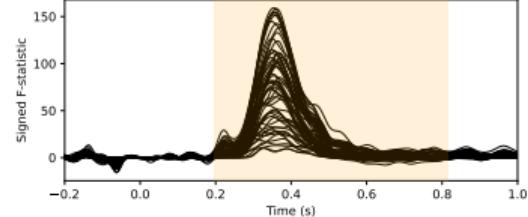
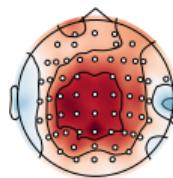


0.088 - 0.274 s



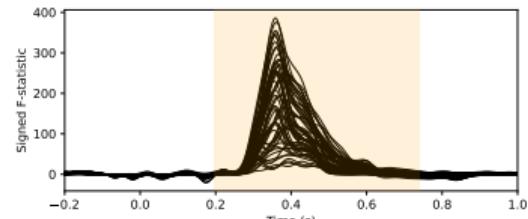
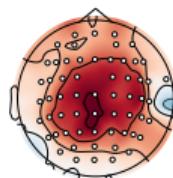
Covert VSA

0.196 - 0.812 s



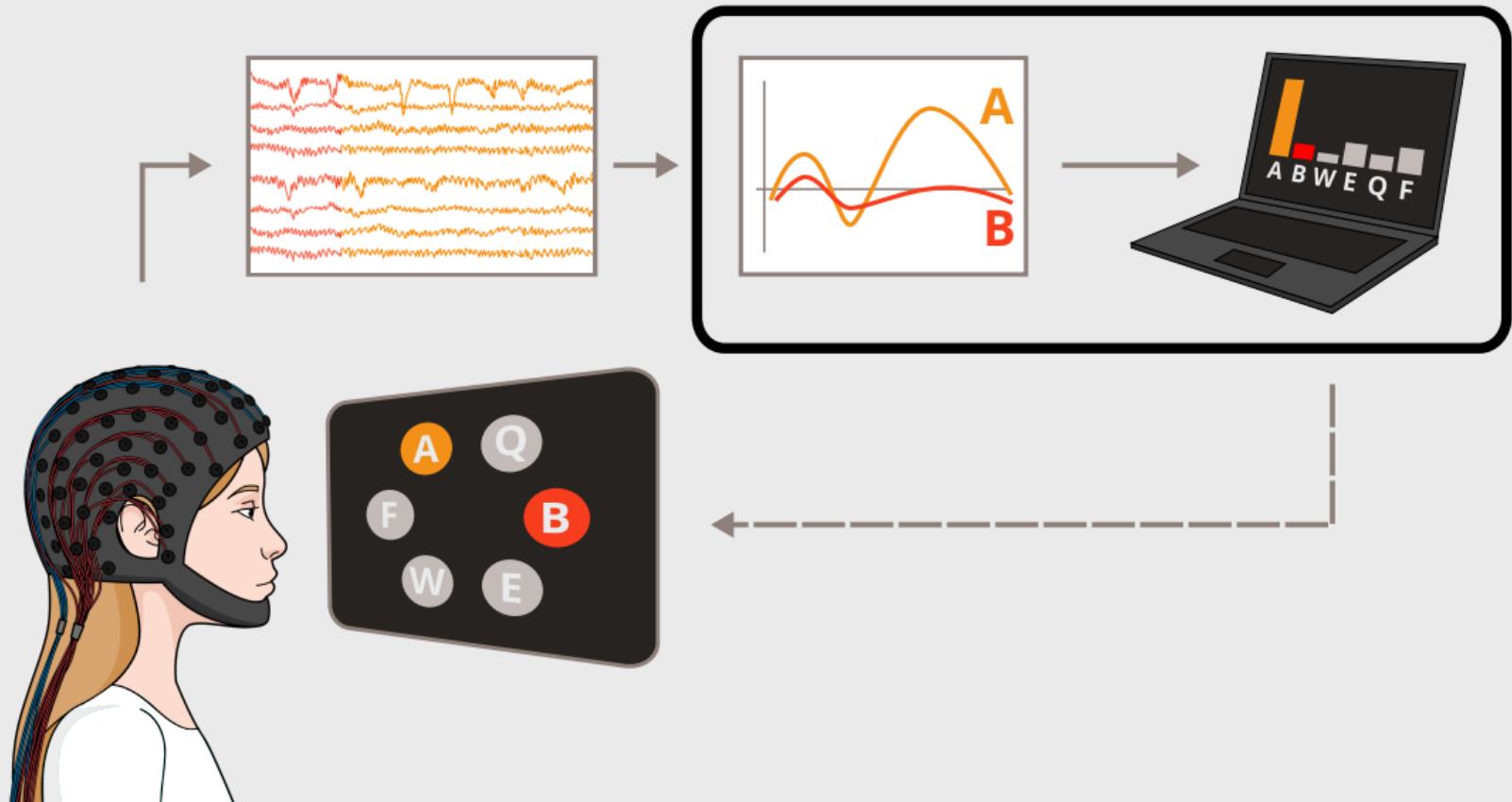
Split VSA

0.198 - 0.740 s

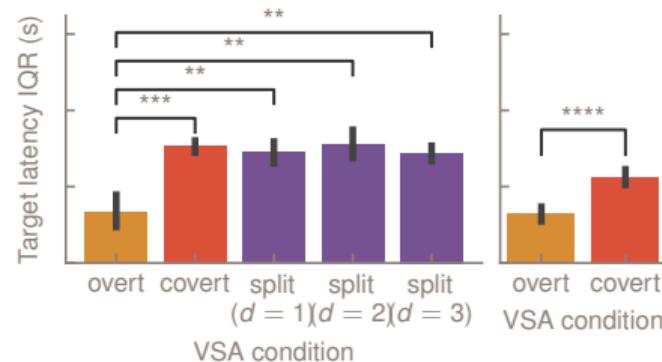
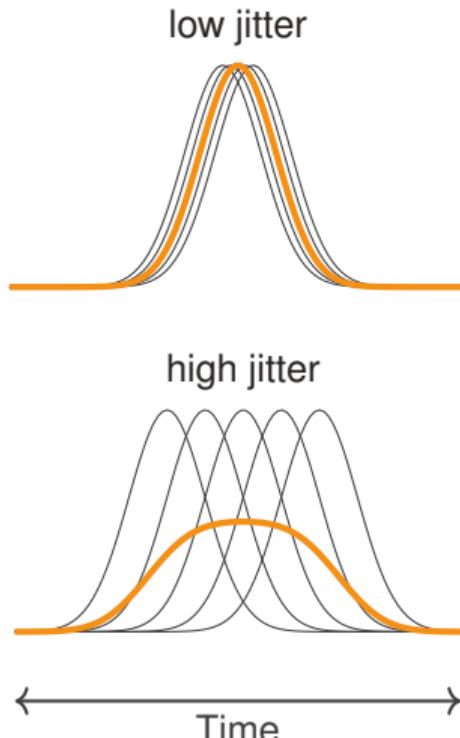


F-statistic cluster-based permutation tests, target vs. non-target

C3. Gaze-independent decoding



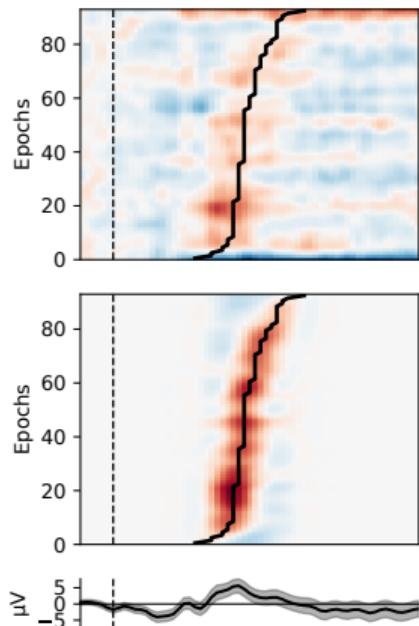
Problem: Latency jitter decreases performance in covert and split attention



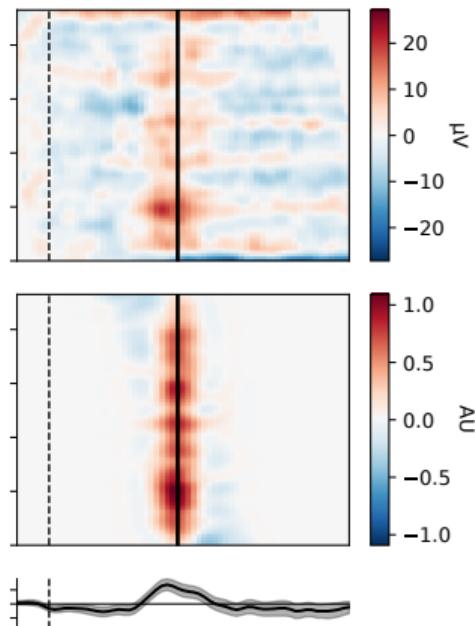
- ▶ Classifier-based latency estimation Mowla et al., 2017
- ▶ Jitter of discriminative information is higher for gaze-independent settings
- ▶ Contributes to low accuracy Aricò et al., 2014
- ▶ **Can this be exploited?**

Latency estimation and alignment

Before alignment



After alignment

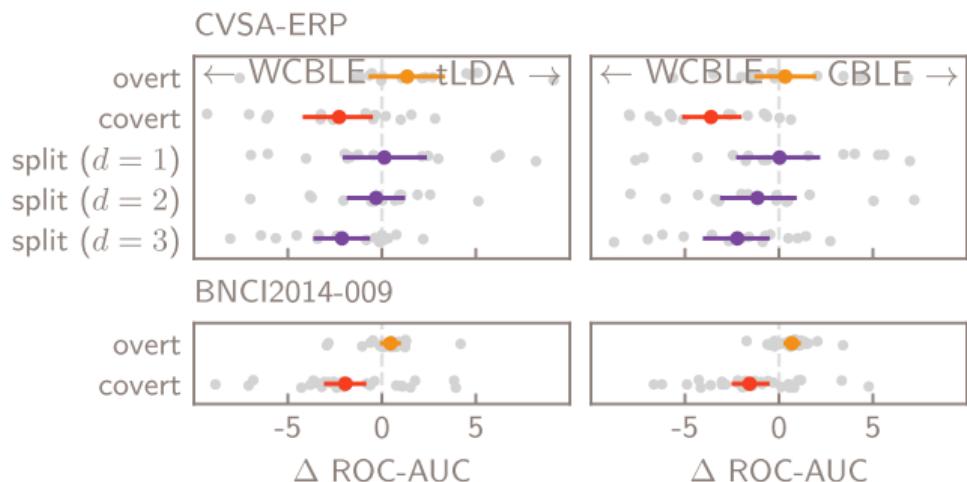


Developed iterative method based on CBLE

Enhances latency estimation and SNR in simulated data

Does this transfer to real data?

Application to gaze-independent decoding



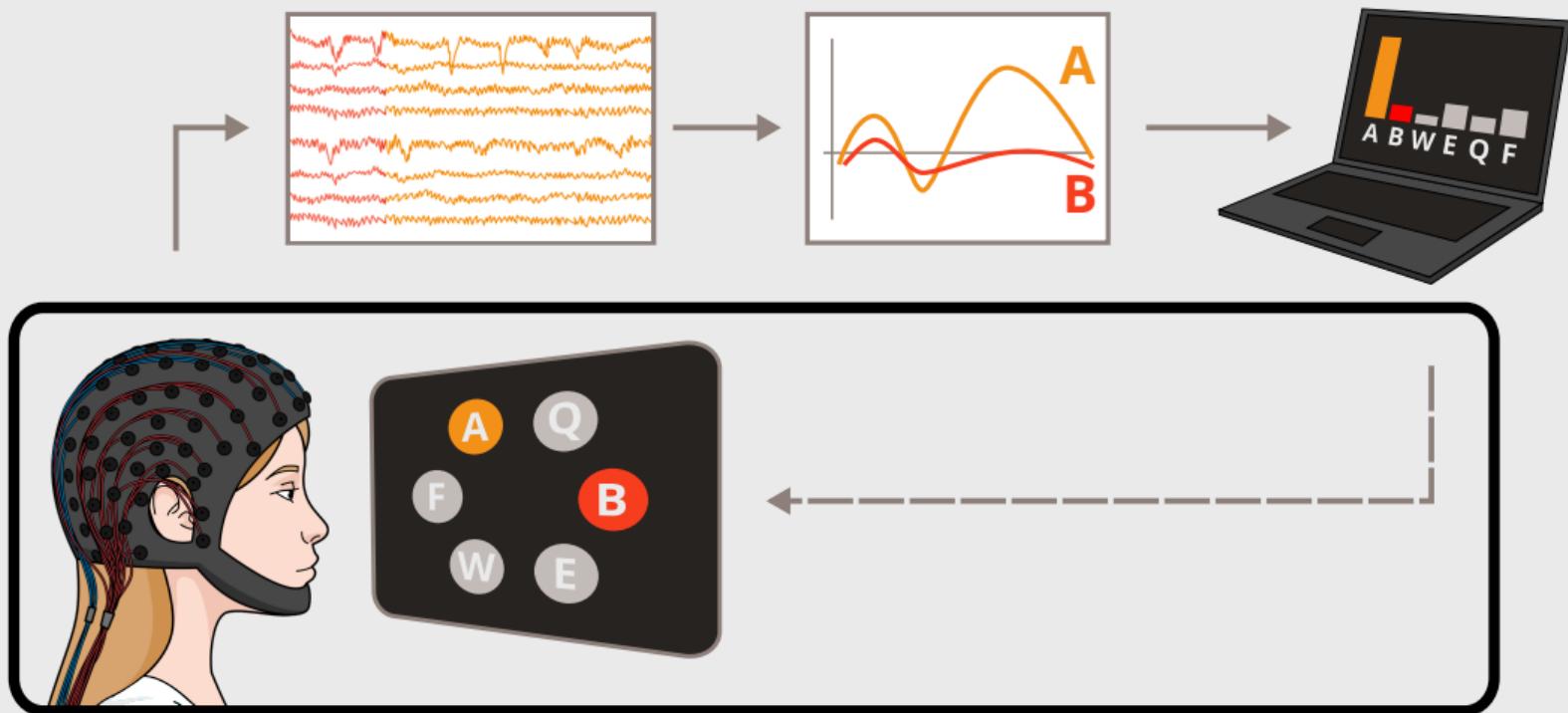
Iterative CBLE can function with unseen data and is applicable as decoder

Within-subject, cross-validated single-trial ROC-AUC (%)

Within and across VSA conditions to establish independence

Improves decoding performance in gaze-independent settings

C4: Evaluation in end-users



Recruited individuals with physical, speech and eye movement

3 Friedreich's **ataxia**

- ▶ impaired speech
- ▶ involuntary eye movements
- ▶ discomfort fixating

1 bulbar onset **ALS**

- ▶ no speech
- ▶ minor eye movement impairment

3 brain stem or cerebellar **stroke**

- ▶ no speech
- ▶ partial eye paralysis

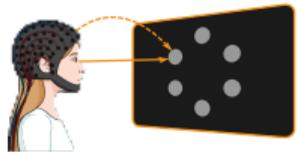
Large **individual variety** in preserved skills



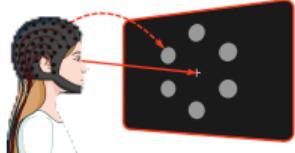
Off-line covert vsa experiment



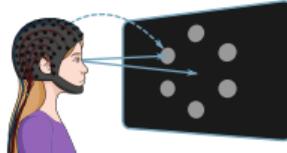
Overt VSA



Covert VSA



Free VSA



EEG, EOG and eye-tracking

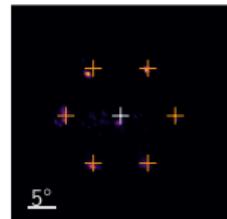
Adapted stimulation parameters

Few studies investigating VSA abilities of end-users

Replace *split* by *free* to study comfort

Eye tracking

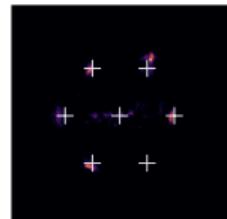
PA1, overt VSA



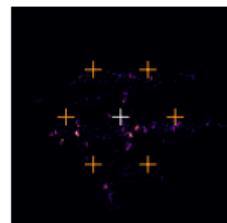
PA1, covert VSA



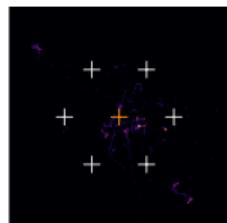
PA1, free VSA



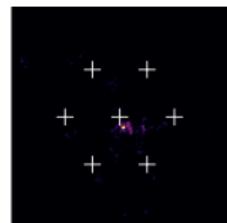
PB2, overt VSA



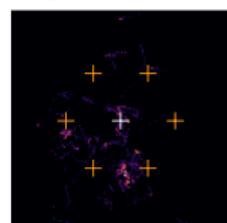
PB2, covert VSA



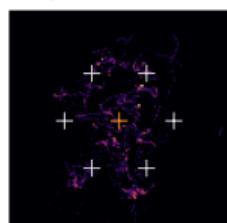
PB2, free VSA



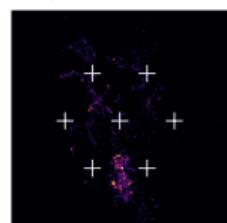
PC4, overt VSA



PC4, covert VSA



PC4, free VSA

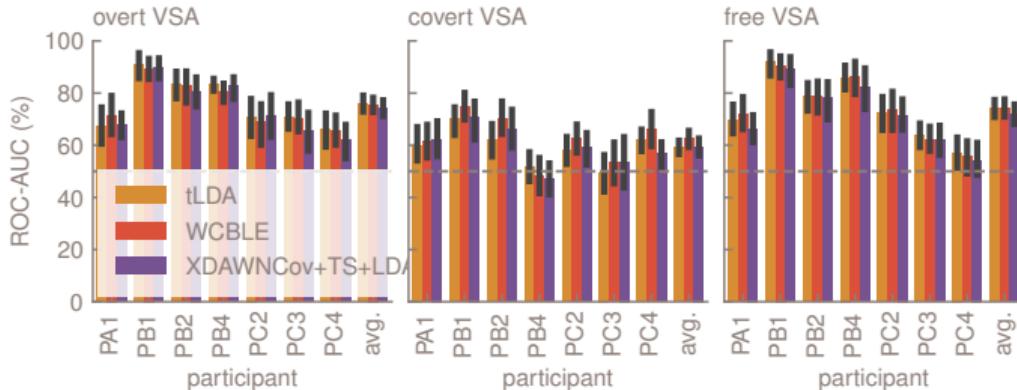


Most preferred to perform overt VSA

Voluntary covert and split VSA did occur

Portable eye tracker not always suited

Subject decoding performance



Off-line decoder comparison

All but one subject above chance

Covert was lower than overt, free generally on par

Limited impact of gaze-independent decoding

Contribution of gaze, break with limits of overt and covert

Recap

1. Visual, spatial ERP paradigm
2. 2 decoders exploiting spatiotemporal structure
3. Covert attention study with healthy subjects
4. Iterative alignment decoder for gaze independence
5. Off-line study with eye-motor impaired patients

Publications

Conclusions

- ▶ Improved decoders enhance BCI **efficiency**.
- ▶ Applications to gaze-independent decoding improve **inclusivity**.
- ▶ Limited effect on end-users
- ▶ Gained insight in requirements of BCI users with gaze-impairment

Perspectives

- ▶ Models capturing multi-component and non-stationary aspect of (covert) ERPs
- ▶ On-line experiments
- ▶ User experience study
- ▶ Integrate EEG and eye-tracking

Q&A

Experimental procedure CVSA-ERP

hardware, locations, timings, nr of blocks, ...

Experimental procedure end-user study

hardware, locations, timings, nr of blocks, ...

Block-term tensor discriminant analysis procedure

backward model image and equation

forward model image and equation

deflation image and equations

model selection procedure

Block-term tensor discriminant analysis procedure

backward model image and equation

forward model image and equation

deflation image and equations

model selection procedure

Subjects with physical, speech and gaze impairment

ID	Diagnosis	Age	Speech	Trach.	Communication
PA1	bulbar-onset ALS	58	absent	no	tablet
PB1	Friedreich's ataxia	41	impaired	no	verbal
PB2	Friedreich's ataxia	43	impaired	no	verbal
PB4	Friedreich's ataxia	48	impaired	no	verbal
PC2	brainstem stroke	43	absent	yes	eye movement
PC3	brainstem stroke	43	absent	yes	letterboard
PC4	cerebellar stroke	54	absent	yes	letterboard

Eye motor impairment

	PA1	PB1	PB2	PB4	PC2	PC3	PC4
Visual fixation	x	x	x	x	x	x	x
Eyelid function						x	x
Ocular motility		x		x	o	o	x
Binocular vision					x	o	o
Field of vision						x	x
Involuntary movement		x	o	x	x	x	

x: impaired, o: severely impaired

User-Centered Design

	Principles
P1	understand user, task, environment
P2	early and active user involvement
P3	driven by user-centered evaluation
P4	iterative design
P5	address holistic experience
P6	multidisciplinary design